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Double Negative Left-Handed Metamaterials for Miniaturization of Rectangular Microstrip Antenna

Ghanshyam Singh

Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Solan, India.
Email: drghanshyam.singh@yahoo.com

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ABSTRACT

In this paper, I have explored a significant concept for the miniaturization of microstrip patch antenna configuration by using the double negative (DNG) left-handed Metamaterials, which have dielectric permittivity and magnetic permeability both negative, simultaneously. It is achieved through the concept of phase-compensation by thin slab consist of the double positive (DPS) material, which have dielectric permittivity and magnetic permeability both positive, simultaneously and DNG metamaterials as a substrate of the microstrip patch antenna. By combining the DNG metamaterial slab with the slab made of DPS materials form a cavity resonator whose dispersion relation is independent of the sum of thickness of the slabs filling this cavity but it depends on the ratio of their thicknesses. This cavity constitutes by DPS and DNG material is used as substrate of the microstrip antennas and the DNG material slab is behave as phase compensator.

Keywords: Microstrip Antenna, Phase Compensation, Metamaterials, Double Negative Metamaterials

1. Introduction

Recent trends of the wireless mobile communication technology are towards the miniaturization and demand for more robust and compact designs have been growing [1-5]. However, in the wireless communication systems, an antenna still remains a matter of concern regarding to its size. Although, a certain level of maturity have been attained. The microstrip patch antennas, due to their inherent capabilities such as low profile, conformability, low-fabrication cost, mechanical robustness, polarization agility, compatibility/easy integration with microstrip circuits/solid state devices and adaptability to active antenna elements are widely used in all the wireless mobile communication systems. Typically, the size of a microstrip patch antenna is depends on the wavelength corresponding to its resonant frequency. There are several other factors that contribute to deciding the dimension of the antenna and its behavior such as the used substrate material and its thickness [3,4]. Literature results show that the use high-dielectric constant substrates [6], shorting walls [7], shorting pins [8,9], are effective ways for the size reduction. But the cross-polarization of such antenna is usually very high which may not be suitable for some applications [10].

The rectangular patch microstrip antenna is consists of a conductive patch on substrate materials above a conductive ground plane as shown in Figure 1. The excitation of the patch is accomplished via a microstrip feedline. This feed technique supply the electrical signal to the patch which will be converted to an electromagnetic wave. The present paper explores the possibility of miniaturization of the rectangular microstrip patch antennas using a substrate material consists of DPS and DNG metamaterials. This paper is organized as follows. The Section 2 is concern with the concept of the phase compensation. The Section 3 discusses the effects phase compensation on the size of the rectangular microstrip patch antenna and finally, Section 4 concludes the work.

2. Phase Compensations

Recently, there has been growing interest in the metamaterials with negative permittivity and permeability as candidate for design of the novel microwave and optical devices [1-5,11-19]. We can view metamaterials as a broader class of materials than left-handed medium. It is a class of materials that enable us to manipulate the di-
electric permittivity and magnetic permeability. An electromagnetic wave propagating through such a material has a Poynting vector anti-parallel with its phase velocity vector as demonstrated theoretically by Veselago [17]. Such materials have been constructed in microwave range by the Smith et al. [18]. The double negative metamaterial represents a new kind of artificial dielectric media which are usually synthesized using periodic structures and exhibits the negative refractive index characteristics (resulted from simultaneous negative permittivity and permeability). Such a material have been referred to as several other names such as left handed materials, metamaterials and backward wave materials [13,16,19]. The DNG material unit cell employs split ring resonators and thin wires. Thin wire structures produce effective negative dielectric permittivity below the plasma frequency and the split-ring resonators can result in an effective negative permeability over a particular frequency range. Overlaying these two frequency regimes, both the permittivity and permeability are simultaneously negative thus the index of refraction may have negative real value over a pass band region. By manipulating two structures the effective permittivity and permeability can be changed separately, giving us the capability to control the position of double negative regime. Several theoretical and experimental setups have been constructed on wave reflection and refraction at an interface between a backward wave medium and positive parameter medium and radiation from traveling wave source at such interface. Engheta [14] analyzed one dimensional cavity resonator made of two cascaded planar layers of backward wave and conventional dielectric, which are placed between two perfect reflectors. Because the phase velocity in DNG slab is opposite to that in DPS layer, the DNG slab acts as phase compensator. Thus, the phase cancellation can occur, leading to resonance, when the phase changes in the two layers are equal in magnitude but opposite in direction. Thus, it turn out that the condition for resonance does not depend on the thickness of two layers but rather on their ratio. This allows one, in principle to reduce the total thickness of the resonator and will as long as the required ratio of thicknesses is maintained [13-15]. The important potential application of this concept is the antenna miniaturization.

Consider a wave traveling through two consecutive slabs as shown in Figure 2. It would experience a phase change say positive in the DPS material and a negative (opposite) phase change in the DNG material. The slab thicknesses can be adjusted to nullify the positive and negative phase shifts in the cavity formed by DPS and DNG materials so that a phase compensated resonator has to be independent of the $\lambda/2$ constraint [3]. This property of phase-compensation demonstrates the possibility of size reduction for patch antenna on a combined DPS-DNG substrate. There are two configurations of rectangular microstrip patch antenna with a DPS-DNG substrate have been considered.

1) The interface between the two regions is parallel to the radiating edges, and

2) The interface between the two regions is normal to the radiating edges.

For the configuration, where the DPS-DNG interface is normal to the radiating edge is has been shown through simulation that the antenna is a poor radiator [4,14]. The present work focuses on the case where the interface is parallel to the radiating edge. I have used the cavity model with two electric walls (PEC) and four magnetic walls (PMC) as shown in Figure 1.

The slab of conventional lossless DPS materials with positive index of refraction $n_1$ of thickness $d_1$ and another slab of the lossless DNG metamaterials with negative refractive index $-n_2$ (due to double negative metamaterial) and thickness $d_2$. We assume that each of these slabs is impedance matched to the outside region. Let us take a monochromatic uniform plane wave normally incident on this pair of slabs as shown in Figure 2. As this wave propagates through the slab, the phase difference between the exit and entrance faces of the first slab is $n_1 k_0 d_1$, where $k_0 = \omega \sqrt{\epsilon_0 \mu_0}$, while the total phase difference between the front and back faces of these two layer structure is $[n_1 k_0 d_1 - n_2 k_0 d_2]$, implying that whatever the phase difference is developed by traversing the first slab is can be compensated by traversing the second slab. If the ratio of $d_1$ and $d_2$ is chosen to be $d_1 / d_2 = \left| n_2 / n_1 \right|$ at the given frequency, then the total phase difference between front and back faces of these two layer structure will become zero. This means that the DNG slab acts as phase compensator in this structure [14,15]. We should note that such phase compensator does not depend on the sum of the thicknesses $d_1 + d_2$, rather it depend on the ratio of $d_1$ and $d_2$. Thus, in principle, $d_1 + d_2$ can be any value as long as $d_1 / d_2$ satisfies the above condition. Therefore, even though these two layer structure is present, the wave traversing this structure would not experience the phase difference. This feature can lead to several investing ideas in devices and component designs. This concept of a miniaturized cavity resonator can be extended to a 3-D cavity and further to a microstrip patch antenna through the cavity model. The rectangular microstrip patch antenna that has been considered in this work is placed on a DPS-DNG combined slabs as substrate as shown in Figure 1. The 1-D sub-wavelength cavity resonator (SWCR) as it is termed consists of two slabs, one DPS and one DNG, between two PEC (perfectly conducting) walls, where the plane $z = 0$ is taken to be at the perfectly conducting...
Figure 1. 3D view of DPS-DNG substrate for a rectangular microstrip patch antenna

Figure 2. 1D cavity resonator made with DPS-DNG combination

The idea of left-handed double-negative material as stated earlier is that when a uniform plane wave is launched in such a medium, it will have a phase velocity opposite to that of its Poynting vector. The phase velocities, in principle, are realized by combining the slabs of usual materials and a metamaterials with negative permittivity and permeability. The size of radiating edge of the patch is approximately half of the wavelength in free space for the resonant frequency of the cavity. In this configuration, the frequency dependence of the reflection coefficients from the resonator is not determined by the resonator size, but by the frequency dependence of the material parameters. This means that we deal with resonance of inclusions (split ring resonator etc.) and not by the cavity resonance (the resonator size can be further reduced if only one separate inclusion is used as resonator) as shown in Figure 3. The resonance frequency of the cavity consists of DPS and DNG materials is down-shifted compared to the resonance frequency of cavity made of DPS materials. Due to this down-shift of resonance frequency, the cross-section of the radiating structure is reduced significantly. The shift in the resonant frequency to a lower value with metamaterial is promising because it suggests a reduction in the patch size as shown in Figure 3. The width of DPS slab (taken as substrate) material \(d = d_1 + d_2 = 28.33\) mm with relative permittivity 5.9 and permeability is 1.0. When the DPS and DNG have been taken as slab then \(d_1 = 17.45\) mm and \(d_2 = 10.89\) mm (metamaterial), respectively.

For the simulation, I have used CST Microwave Studio which is based on finite integration technique (FIT) for general purpose electromagnetic simulator. FIT is applied to cartesian grids in the time domain is computationally equivalent to the standard finite difference time domain (FDTD) method [20]. For high frequency electromagnetic applications, time domain simulation methods are highly desirable, especially when broadband results are needed. An antenna bandwidth is mainly determined by the materials resonance response and not by the antenna size. For example, a desired resonant frequency of 10GHz the patch size without CSRR (complimentary split ring resonator) is 139.16 mm\(^2\) and with CSRR it is 70.85 mm\(^2\) resulting in a forty nine percent size reduction as shown in Figure 4. Certain design has a significant patch size reduction. In addition, the back lobe radiation is negligible and directivity is comparable to the traditional microstrip antennas, whose substrate is positive. It is observed that the certain designs have a significant patch size reduction and have a negligible back lobe in the radiation pattern. It shows that new kind antennas will get similar radiation patterns to the ones of conventional...
right-handed microstrip antennas in some case, and can yield novel radiation patterns of low elevation angles and low side lobes in other cases. These brand new radiation patterns are hardly achieved by conventional right-handed microstrip antennas. By employing the substrate partially filled with double negative medium, the dimensions of the patch antenna could be significantly miniaturized, and the calculated results for the patch length 0.2 λ show that although the use of practically dispersive double negative medium could not support such broadband performance as hypothetical non-dispersive double negative medium, but it proves the approach is perspective and important for the miniaturization of the patch antenna.

4. Conclusions
The size reduction of microstrip patch antennas using left-handed materials has been achieved through the concept of phase-compensation by implementing a combined DPS-DNG substrate. By employing the substrate partially filled with double negative medium, the dimension of the patch antenna could be significantly miniaturized. Many researchers are trying to improve the performance of microwave, wireless communications, microelectronics, and optical devices using these new metamaterials. As the demand for small size, lightweight, and low-cost communication devices continues, the use of low-cost, small-size patch (or microstrip) antennas asserts itself. There are several variables contribute to the resonance frequency of the CSRR. An extensive study of the variable dependence will enable a designer to choose the appropriate CSRR for a particular patch antenna. A further study of radiation efficiency and bandwidth of such antennas is underway.

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REFERENCES


A Novel Over-Current Protection Technique Applied to Peak-Current Type DC-DC Converter

Yu Fang1, Tengfei Wei1, Liang He2, Yong Xie1, Yan Xing2

1College of Information Engineering of Yangzhou University, Yangzhou, China; 2Aero-Power Sic-Tech Center, Nanjing University of Aeronautics and astronautics, Nanjing, China.

Email: yfang@yzu.edu.cn, {yzxieyong, hbweitf}@126.com, xingyan@nuaa.edu.cn

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ABSTRACT

The change of the over-current protection point of the power switches, caused by slope compensation, is analyzed in detail. It is discovered that the peak current protecting value increases as the duty cycle decreases. As a result, the safety operation of the switches is damaged greatly. A novel solution to improve over-current protection with constant peak current limitation is proposed by inducing synchronous slope compensation into the current limit function instead of the original constant voltage. The design principle and method of the protection circuit based on a UC3846 PWM controller for the interleaved dual-forward converter is presented. Experimental results are given to verify the analysis.

Keywords: DC-DC Converter, Peak-Current Control, Constant Peak-Current Limiting

1. Introduction

The control method for high-frequency DC-DC converters can generally be put into two categories: voltage-controlled converters and current-controlled converters. Current-type control can also be further divided into peak current and average current control [1]. Peak-current regulation is widely applied because it has the following advantages [2]: perfect linear control and fast dynamic response, the cancellation of the second-order pole and the attainment of the first-order system, and the simplification of over-load and short-circuit protection due to pulse-by-pulse current limiting. In addition, the current share is easy to implement if controlled by current mode. However, slope compensation is needed to achieve a state system when duty cycle $D > 0.5$ [3]. At the same time, the introduction of slope compensation will cause a limited amount of current through the switches to lessen as the duty cycle decreases, so the rated voltage of switches cannot be employed sufficiently.

This paper will be focused on the above question and give an improvement on accomplishing the constant current-limiting value. The proposed method is to combine the slope compensation signal with the current-limiting circuit in order to achieve constant peak current limiting value in the wide range of the duty cycle.

2. Peak Current Control

2.1 The Analysis of the Stability and Slope Compensation

It is well-known that PWM is achieved by comparing the sensed inductor current with the output of the voltage regulator, as illustrated in Figure 1. The relationship between system stability and duty cycle is demonstrated in Figure 2.

Figure 2(a) and Figure 2(b) correspond to a duty cycle of less than 0.5 and more than 0.5 respectively. From Figure 2, we can derive expression (1). Assuming that $\Delta i_L$ is initial disturbance quantity, the expression (2) is obtained.

$$D = \frac{m_2}{m_2 - m_1} = \frac{|m_2|}{|m_2| + |m_1|}$$  \hspace{1cm} (1)

Assuming that $\Delta i_L$ is the initial disturbance quantity, expression (2) is obtained.

$$\Delta i_L = -\Delta i_L m_2 / m_1$$  \hspace{1cm} (2)

It can be seen that $\Delta i_L$ gets smaller when $D < 0.5$ ($|m_2| < |m_1|$) and the system is stable after a switching period, while $\Delta i_L$ gets larger when $D > 0.5$ ($|m_2| > |m_1|$) and the system unstable after a switching period.

In order to make the system stay stable, the slope com-
A Novel Over-Current Protection Technique Applied to Peak-Current Type DC-DC Converter

Figure 1. Schematic diagram of peak current control

Figure 2. Responses of $i_L$ to disturbance on different $D$

compensation should be employed [4,5]. As usual, there are two methods that can be used to implement the slope compensation: in the first the sum of $V_e/RS$ and slope -$m$ is compared with the current through the inductor, as illustrated in Figure 3(a); in the second the sum of the current of the inductor and slope $m$ is compared with $V_e/RS$ as in Figure 3(b).

Taking Figure 3(a) as example, the response to the current disturbance can be shown in expression (3) after compensation.

$$\Delta I_i' = -\Delta I_i (m + m_2) / (m + m_1)$$

(3)

It can be concluded that $-(m + m_2) / (m + m_1) < 1$, i.e., the condition of $m > -0.5$ should be met, because $\Delta I_i' < \Delta I_i$ in a stable system.

2.2 Peak Current Protection Issue Caused by Slope Compensation

Based on the above analysis, the slope compensation can make the system controlled by peak current easier to stabilize even though $D$ is greater than 0.5. However, slope compensation causes the maximum current limiting value to vary when the duty cycle changes. This is bad for those systems in which the given voltage and current need to change, such as a plating power supply. Because the duty cycle needs to change in these systems, the switch will bear a heavy burden of current stress. Hence, in order to guarantee switch safety we must choose a highly rated switch, which raises the design cost.

Taking the example of Figure 3(b), the compensation function can be expressed as Equation (4) during the time interval of $t_{on}$:

$$i_{ct} = I_{cto} + m \frac{t}{T} (t \leq t_{on})$$

(4)

where, $i_{ct}$ is instant compensation value, $I_{cto}$ is the minimum of the slope compensation value, and $m$ is the slope rate of the compensation function.

As usual, the maximum value of the sampled current, i.e., over-current-protect point is set as a constant $I_{LIM}$. Hence, what we limit is the sampled current value after slope compensation, and the actual peak current limiting value should be calculated by expression (5).

$$i_{acm} = (I_{LIM} - I_{cto} - mD) / n$$

(5)

where, $n$ is the turn ratio of the current transformer. As can be seen from expression (5), the current limiting value is higher when $D$ is smaller, while the current limiting value is lower when $D$ is larger. It is clear that peak current limiting value differs when $D$ differs, and the current through the inductor can get very high when $D$ is near to zero. Based on this analysis, we know that there is a conflict between safe use and full use of a switch after utilizing slope compensation. The following section will propose a solution to this conflict.

3. Proposed Constant Peak Current Limiting

3.1 Operation Principle

In order to make the limited current value through a switch not to change with duty cycle $D$, we propose that the current with the same slope as the compensating current should be added to the original current limiting value. Hence, the increment caused by slope compensation should be cancelled out, so the constant peak current limiting value through the inductor can be obtained. The concrete technique is to import the slope compensation waveform in Figure 4 to the maximum current limiting pin of PWM control chip. Thus we can obtain the current limiting value, as seen in Equation (6).

$$i_{lim} = I_{LIM} + m \frac{t}{T}$$

(6)

Substituting (6) for $I_{LIM}$ in (5), we get (7). Seen from Figure 4 and Expression (7), $i_{lim}$ is independent of $D$ and only dependent on the initial value of slope compensation and current limiting value, as a result of the fact that constant peak current limiting value has been achieved.

Taking the example of Figure 4(b), the compensation function can be expressed as Equation (4) during the time interval of $t_{on}$:

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Figure 3. Principle of slope compensation
3.2 Implementation Circuit

Figure 5 shows the schematic circuits of slope compensation accompanying constant peak current limiting. This scheme has been successfully applied to two-chokes-interleaving forward converter with UC3846 [6,7]. The slope compensation signal is attained from CT pin of UC3846, which generates saw-tooth waveforms. As seen in Figure 5, the constant peak current limiting signal is also obtained from CT. RP and RT depend upon R3, R4, R5 and RS in the slope compensation circuit. In order to cancel out the effect on current limiting caused by slope compensation, the increments of the two inputs in the comparator should be equal. Considering the three-times-gain current operator in UC3846, expression (8) is given to determine the resistors Rp and RT.

\[ V_{CT} \times \frac{R_T}{R_P + R_T} = V_{CT} \times \frac{R_4 + R_5}{R_4 + R_5 + R_3} \times 3 \]  

4. Experimental Results and Analysis

A dual-forward converter prototype, shown in Figure 6, is built to verify the proposed method [6,7]. The output of the prototype can be regulated from 0 V and 0 A to 6 V and 150 A. The current through the switches or inductor is sensed by a current transformer and the resistor RS in Figure 5 to achieve peak-current control. The high-frequency power transformer is designed as N1 : N2 = 42 : 1 and the turn ratio of the current transformer for sensing is 1 : 100. Figures 7(a)-(d) show the waveforms of sampled current after slope compensation and voltage waveforms from the current limiting pin corresponding to different values for D.

In Figure 7, CS+ is a waveform after adding slope compensation (corresponding to CS+ in Figure 5). Ilim is the waveform of the current limiting pin (corresponding to Ilim in Figure 4 and in Figure 5). D is the duty-cycle waveform of UC3846. As can be seen from Figure 7, the instant current limiting value rises with the switches conducting time increases, and the slope of its waveforms is the same as that of the slope-compensation current. Hence it can be concluded that the increments added to the two inputs in the comparator of UC3846 are counteracted and constant peak current limiting is accomplished.

Due to the fact that the current ripples through the filter inductor and the magnetic current of power transformer are very small in the application circuit, the average current through these switches during the on time interval can be considered to approximately equal to their peak current IPK. So we get:

\[ I_{PK} \approx I_{OLM} \times N_2 / N_1 \]  

where, I_{OLM} is the output current limiting value (measured value) at different duty cycles, and IPK is the peak current value (calculated value); these are listed in Table 1.

Figure 8 shows the current limiting values using conventional methods (the current limiting pin being connected to constant voltage) and using the proposed constant-peak-current-limiting method correspondingly. In Figure 8, curve I represents the limiting value in the conventional method, while curve II represents the proposed method in this paper. As is seen from Table 1 and Figure 8, the current limiting value almost stays constant although the duty cycle is different.

<table>
<thead>
<tr>
<th>Table1. Peak current limiting value vs. duty cycle</th>
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<tr>
<td>D</td>
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</tr>
<tr>
<td>0.2</td>
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<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
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<tr>
<td>0.75</td>
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Figure 5. Schematic diagram of slope compensation & constant peak current limiting

Figure 6. Dual-forward converter
Figure 7. Waveforms of inductor and current limiting pin at different $D$

Figure 8. Peak current protecting points (I1-conventional method, I2-proposed method)

However, it seems that the proposed method does not achieve complete constant peak current limiting values; this is because the concerned resistors do not match well and they cannot proportionally change with each other when operation. This can be improved by optimizing $R_T$. Additionally, it is the main reason that the inner PNP transistor’s affection of UC3846 is not considered in light of the expression (8). The PN junction voltage drop influence much more when the duty cycle is small. With regard to this factor, we are braving the storm.

5. Conclusions

The proposed method in this paper implements constant-peak-current-limiting value. The implementing circuits are very simple and easy to accomplish, the additional cost is almost zero, and furthermore the full use of the rated switch can save cost. Next step how to make the current-limiting value complete constant is the aim.

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REFERENCES


Optical Constants for MBE n-Type GaAs Films Doped by Si or Te between 1.50-4.75 eV

Svetlana N. Svitasheva

Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia.
Email: Svitasheva@thermo.isp.nsc.ru

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ABSTRACT

The thickness and spectral dependence of the complex refractive index of upper layer in thin-film MBE-grown GaAs heterostructures were calculated basing on a classical oscillatory model of dielectric function from spectra measured by spectroscopic ellipsometry (nondestructive, contactless optical method) in the range of 1.5-4.75 eV.

Keywords: GaAs, Heterostructure, Optical Properties, Thin Films, Spectroscopic Ellipsometry

1. Introduction

High-frequency (GHz) transistors and integrated circuits on the A3B5-type semiconductors are commonly used in mobile and satellite communication devices, and also in on-board radar stations owing to their small weight and high efficiency. At present, microwave transistors based on MBE-grown heterostructures have the best parameters.

Bakarov et al. [1] developed a technology for producing heteroepitaxial n⁺-GaAs/n-GaAs/GaAs structures for powerful MESFET microwave transistors with a specific output power of 0.8 W/mm and n⁺-GaAs/AlGaAs/n-GaAs/GaAs structures for powerful HFET microwave transistors with a specific output power of 0.9 W/mm at 17.7 GHz.

The gate width of these transistors is usually 0.13-0.50 µm, whereas the length is about fractions of millimeter. The active layer thickness is 0.15-0.30 µm and the doping level is within (1-5) × 10¹⁷ cm⁻³.

The requirements imposed on an epitaxial layer can easily be formulated according to functional properties of a device (although, it is extremely difficult to satisfy them) [2]:

1) the buffer layer must contain the minimal number of shallow- and deep traps and ensure a spatially sharp barrier of a desired height for electrons in the channel;
2) homogeneity of thickness and doping level of the active layer must be ultimately high.

At optimizing of the modes of growth of separate layers, for monitoring their parameters are usually used the following techniques: low-temperature photoluminescence, Hall, and C-V measurements. However, working structures control requires nondestructive and contactless methods. We suggest to pay attention to application of spectroscopic ellipsometry between 1.50-4.75 eV for restoration of thicknesses and optical constants of layers included into heterostructure (Figure 1).

2. Substantiation

The energy of the GaAs edge self-absorption at a room temperature is 1.425 eV. Since this semiconductor is a direct gap semiconductor, the absorption drastically grows near edge self-absorption, and for the photon energy hv ≈ 1.6 eV the absorption coefficient α = 4πk/λ = 10⁴ cm⁻¹ which corresponds to the extinction coefficient k ≈ 0.1. Casey et al. [3] showed that the doping level between

| n-GaAs : Si |
| C₆₀(3.0-3.5) × 10¹⁷ cm⁻³ |
| 0.3 µm |
| i-GaAs |
| 0.3 µm |
| SL |
| 20 periods |
| 0.068 µm |
| AlAs 5ML |
| GaAs 7ML |
| AlAs 5ML |
| GaAs 7ML |
| i-GaAs |
| 0.3 µm |
| AGCP - 10 |

Figure 1. Scheme of structure: SL is a superlattice, thicknesses of its layer are given in terms of monolayers (ML). The AGCP-10 substrate is a semi-insulating GaAs. All the structures were grown in the same setup.
(5.9 × 10^{17}) + (3.0 \times 10^{18}) \text{ cm}^{-3} \) appreciably changes the absorption coefficient \( \alpha \) for the n-type GaAs for photon energies between 1.3-1.6 eV, however, the increment of \( \alpha \) may change the sign even in this narrow range (Figure 2).

It is also known that the greatest changes in the optical properties can be registered in the region of critical points, i.e., at energies of interband transitions. In the region of spectrum between 1-7 eV, there are several optical transitions, as shown in Table 1 that contains parameters of a GaAs band structure [4].

However, the present-day representation of the GaAs dielectric function \( \varepsilon \) by the sum of oscillators (1) between 1.5 and 5.5 eV leads to the different values of transition energies [5] (Table 2):

\[
\varepsilon = \varepsilon_1 + i\varepsilon_2 = (n^2 - k^2) + i2n\kappa \\
\varepsilon(E) = 1 + \sum_{i} A \left( \frac{1}{E + \varepsilon_i + i\Gamma_i} - \frac{1}{E - \varepsilon_i + i\Gamma_i} \right) 
\]

where \( \varepsilon_i \) is energy and \( \Gamma_i \) is the damping factor of \( i \)-the oscillator, respectively.

In above mentioned tables there are marked oscillators (borrowed from [4,5]) whose energies are beyond the range of our measurements. Therefore, the most interesting regions for our investigation are between 3.0-3.5 eV and in the vicinity of 4.5 eV.

In the region of weak absorption between 1.5 and 2.4 eV, we should expect appearance of an interference effect in the spectra because thickness of the GaAs layer (0.3 m) is less than thickness which in 10 times attenuates intensity of the reflected light, according the Bugger-Lambert law, and the last is changing from 2.57 to 0.4 m.

3. The Goal of Paper

The goal of paper is to determine for MBE-grown n-type GaAs films the spectral dependence of the complex refractive index \( N = n + ik \) and, therefore, complex dielectric function (1). In addition, goal is to calculate thicknesses of two upper layers of the structures and is to show reproducibility of the technological process and on the other hand, is to demonstrate impact of doping level on energy position of critical points too.

4. Experiment

The structures were grown by molecular beam epitaxy in a Riber-32P setup. The substrates were semi-insulating gallium arsenide wafers 40 mm in diameter. The monitoring of growth rate with an accuracy of ±1% was based on registration of intensity oscillations of a zero reflex of the RHEED picture.

Optical measurements were carried out on a Jobin Yvon spectroscopic ellipsometer in the range of photon energies between 1.50-4.75 eV.

The measured spectra of ellipsometric angles \( \Psi(E) \) and \( \Delta(E) \) are related with the relative reflection coefficient \( \rho(E) \) by the identity:

\[
\tan \Psi e^{i\Delta} = \frac{R_p}{R_s} = \rho (E). 
\]

These spectra were corrected using the Drude, Archer, and Saxena [6] relationship (3) by the taking into account of the formed oxide. Herein, \( R_p \) and \( R_s \) are the Fresnel coefficients for p- and s-polarized light; \( \Psi, \Delta \) and \( \Psi, \Delta \) are the ellipsometric angles for structures with a thin (\( d < \lambda \)) oxide and without it, respectively; \( C_{\Psi} \) and \( C_{\Delta} \) are the constants depending on the structure parameters:

\[
\frac{\tan \Psi}{\tan \Psi e^{i(\Delta - \Delta')}} = 1 - iC_{\Delta}d + C_{\Psi}d 
\]
Optical Constants for MBE n-Type GaAs Films Doped by Si or Te between 1.50-4.75 eV

5. Solving the Inverse Problem Ellipsometry

In this paper, we do not consider some aspects of solving the inverse ellipsometric problem (IEP): choosing a calculation technique, the reason of choosing a functional or an error function, etc. A lot of attention earlier has been given to these aspects in works [8-12].

The algorithm of solving the IEP in this paper consists in the division of problem into two parts to determine the parameters of two layers that differ by the doping level:

**Part 1.** In the region of weak absorption, a restoration of six parameters simultaneously: the thicknesses of upper layers \( d_1 \) and \( d_2 \) (see Figure 1) and four parameters of one oscillator describing the dielectric function of the upper layer:

\[
\varepsilon_{\text{trans}}^\mu = \varepsilon_s + \frac{(\varepsilon_s - \varepsilon_\infty)\omega^2}{\omega_s^2 - \omega^2 + i\Gamma_0 \omega}
\]

where \( \varepsilon_s \) and \( \varepsilon_\infty \) are the high-frequency and static dielectric constants, respectively; \( \Gamma_0 \) is the damping factor (\( \Gamma_0 > 0 \)); \( \omega_T \) is the oscillator energy in electron volts, \( \omega \in [1.5-2.6] \) eV. For minimizing the error function of \( \chi^2 \) (which is defined by the difference between the measured value and the value calculated according to proposed model (4)), we used the Marquardt-Levenberg method:

\[
\chi^2 = \frac{1}{2N} \left( \sum_{\tau} \text{Re} \left[ \frac{\varepsilon_{\text{measur}}(\omega) - \varepsilon_{\text{calc}}(\omega)}{\alpha} \right]^2 + \sum_{\tau} \text{Im} \left[ \frac{\varepsilon_{\text{measur}}(\omega) - \varepsilon_{\text{calc}}(\omega)}{\beta} \right]^2 \right)
\]

where \( \alpha \) and \( \beta \) are the weight factors.

**Part 2.** In the region of energies higher than 2.6 eV, where the light penetration depth is much smaller than the film thickness, it is possible to determine the spectral dependence of the dielectric function only for the top layer according to (2) and (6) with regard to the angle of light incidence \( \varphi_0 \):

\[
\varepsilon_{\text{equ}}^\mu = \tan^2 \varphi_0 \left[ 1 - \frac{4 \rho}{(1 + \rho)^2} \sin^2 \varphi_0 \right]
\]

As it has been expected in Substantiation, interference oscillations in spectra of the measured angles and for structures 1, 2, 3 (Figure 3) in the region of weak absorption between 1.5 and 2.6 eV were registered, and their amplitude decreased in according to the increase of photon energy (or of the absorption of MBE GaAs films). Although all the structures were grown in the same setup and in the same regime, the oscillations differ in amplitude and in energy position of its extremums; this fact evidently shows that the properties of at least two upper layers differ; because the contribution of the light reflected by deeper layers is negligibly small. Fragments in Figure 3 show that the \( \Psi \) amplitude, which characterizes the module of the relative reflection coefficient \( \rho \), varies between 10-17°, whereas the phase of \( \Delta \) of the complex \( \rho \), or the difference phases of \( R_p \) and \( R_s \); \( \delta_p - \delta_s = \Delta \), changes from 160 to 182°. At the same time, the positions of the first maximum in \( \Psi \) are 1.65, 1.70, and 1.50 eV for the first, second, and third samples, whereas

Figure 3. Experimental spectral dependences of \( \Psi \) and \( \Delta \) for three structures with correction of oxidation effect (\( d \approx 13 \AA \)). Oscillation of \( \Psi \) and \( \Delta \) in the region of weak absorption are fragmented. A semi-insulating GaAs spectra are shown for comparison [5].
the positions of the first minimum in $\Delta$ are 1.67, 1.75, and 1.65 eV, respectively. Thus, even without calculating, it is clear fact that spectroscopic ellipsometry possessing high phase sensitivity makes it possible to detect the difference in the properties of the structures under investigation.

6. Results and Discussion

In order to find values of these dissimilarities, it is necessary to solve IEP by calculation of Fresnel coefficients for all layers shown in Figure 1.

The thicknesses and spectral dependences of dielectric functions of all layers except for two upper layers are assumed to be known. For describing the unknown function $\varepsilon(E)$ we used oscillator model (4) that involves four unknown parameters. Results of minimizing procedure (5), namely, the thickness, are listed in Table 3.

In Figure 4 the spectral dependences of optical constants $n(E)$ and $k(E)$ (for the region of energies 1.5-2.6 eV) are represented and they show that compared with the bulk semi-insulating GaAs, the real part increases approximately by 5-9%, whereas the imaginary part, that characterizes the absorption, increases by 15% and more, remaining equal to ~0.1 (for a photon energy of 1.54 eV).

The curves of the absorption coefficient are noticeably shifted toward lower energies. The deviations of the to-
tal thickness of two upper layers from the designed value for these samples vary from -7 to +4%, and this fact should be taken into account in a manufacturing of transistors.

The complex refractive index for energies higher than 2.6 eV, which was calculated from (2) and (6), is also depicted in Figure 4. In the vicinity of the first oscillator (see Table 2), the greatest increase of $n$ is not more than 3-9% and the maximum absorption grows by 15-20% compared with the semi-insulated gallium arsenide. Probably, additional levels responsible for increasing number of transitions from valence band to conductance band are formed in the band gap. Generally, influence of a dopant on optical constants of GaAs depends not only on its concentration, but also from type of a doping element, as shown in a Figure 5. It seems that in the region of energies greater than 3.5 eV, curves of $n(E)$ intersect.

Table 3. Calculated thickness of two upper layers shown in Figure 1

<table>
<thead>
<tr>
<th>sample number</th>
<th>$d_{1}$, $\mu$m</th>
<th>$d_{2}$, $\mu$m</th>
<th>$d_{1}+d_{2}$, $\mu$m</th>
<th>$%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2386</td>
<td>0.3187</td>
<td>0.5573</td>
<td>-7.1</td>
</tr>
<tr>
<td>2</td>
<td>0.2896</td>
<td>0.3364</td>
<td>0.6260</td>
<td>+4.3</td>
</tr>
<tr>
<td>3</td>
<td>0.3170</td>
<td>0.2656</td>
<td>0.5826</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

Figure 4. Optical properties of MBE-grown n-type GaAs films doped by silicon (concentration of 3.0-3.5) $\times$ ($10^{17}$) cm$^{-3}$, which were found from the ellipsometric spectra, for the upper structure layer (see Figure 1). Spectra of a bulk semi-insulating GaAs are shown for comparison.

Figure 5. Impact of the doping elements (Si or Te) on dispersion of GaAs optical constants in vicinity of critical point energies. Spectra of GaAs (100) constants are inserted for comparison from [5]. Approximately the same doping level of different elements (Si or Te) influences on GaAs optical constants by other way.
In fact, there are no intersections. This clearly can be seen in the 3D space of the parameters $E$, $n$, and $ik$ in Figure 6. The 3D graph shows movement of the vector of the complex refractive index via function of photon energy. Besides, the level of doping of upper layer causes slight impact on $n + ik$ in the range of great photon energies.

7. Conclusions

We have shown the possibility of determining the spectral dependence of the complex refractive index and the thicknesses of $n$-type GaAs layers with different levels of doping. It is remarkable that in the region of weak absorption (from 1.5 to 2.5 eV) everybody can without calculating evaluate the difference or identity of operating layers, i.e., to evaluate repeatability of structures; this is of particular importance for manufacturing GHz transistors.

8. Acknowledgements

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Figure 6. Spectral dependences of the complex refractive index for the bulk single-crystal GaAs and sample 3 in the 3D space with the vector coordinates $E$, $n$, and $ik$, whose two projections are shown in Figure 4.

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Drive and Control of Electromagnetic Drive Module on Reciprocally Rotating Disc Used for Micro-Gyroscope

Nan-Chyuan Tsai*, Jiun-Sheng Liou, Chih-Che Lin, Tuan Li

Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan, China.
Email: nortren@mail.ncku.edu.tw

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ABSTRACT

An innovative 3-phase AC (Alternative Current) drive circuit for the seismic disc in micro-gyroscopes is designed and verified by computer simulations and experiments. The in-plane dynamic model of the seismic disc with mass eccentricity and air gap against the centre bearing and the mathematic expression of two sinusoidal magnetic fields are developed respectively. In order to prevent the seismic disc from collision with the centre bearing and the EM (Electromagnetic) poles, an anti-collision controller is established by employing two Look-up tables which define the intensity of the applied current to the EM poles. Self-sensing technique is included to measure the real-time offset of the disc by two orthogonal pairs of EM poles, without any additional sensors. The drive circuit under SPWM (Sinusoidal Pulse Width Modulation) operation and the anti-collision strategy are verified by intensive computer simulations via commercial software, OrCAD 9, and experiments.

Keywords: Micro-Gyroscope, Electromagnetic Pole, Anti-Collision, Drive Circuit

1. Introduction

By applying the Coriolis principle, the micro-gyroscope is used to detect and measure the exerted angular excitations [1,2]. The performance of the micro-gyroscope, such as resolution, sensitivity and measurement range, is limited by a few factors, for example, fabrication imperfection, frequency mismatch, and maximum rotational speed of the seismic disc [3,4]. In order to ensure satisfactory performance of gyroscope, the disc has to be properly driven so that high-speed rotation and quick rotation direction switch can be both achieved. If the disc can be driven in the fashion of micro-motor (instead of electrostatic force), the performance of micro-gyroscope can be definitely much improved. That is, the electro-magnetic technique has to be employed, instead of the approach by electrostatic drive which is conventionally adopted.

However, the associated technique on motor-like drive is, to some extent, complicated to be used in micro-systems. The maximum torque for any one of the aforesaid motors [5,6] is of the order in “pN-m”. Therefore, by employing the 3-phase AC drive technique and the SPWM (Sinusoidal Pulse Width Modulation) operation, a seismic disc can be driven up to 12500 RPM in our work. The design details and fabrication process on the twelve EM (electromagnetic) poles which encloses the seismic disc made of aluminum can be referred to our previous work [7]. This paper is aimed at the drive circuit design and anti-collision strategy for disc against centre bearing. In order to explore how intensive the constructed magnetic fields by the twelve EM poles can be, and what the response of the disc will be, the in-plane dynamic model of the seismic disc with mass eccentricity and air gap against the centre bearing and the mathematic expression of two sinusoidal magnetic fields are established at first.

On the other hand, though various patterns of micro-motors have been successively presented, such as electro-static [8,9], electro-magnetic [10] and piezo-electric [11,12], yet the collision between rotation disc and the bearing has not been deeply discussed and successfully prevented. Nevertheless, this issue gradually becomes an attractive topic in the micro-motor research field. For example, the concept of gas-lubricated bearing has ever been proposed so that the induced gas film can be used as the buffer between disc and bearing [13,14]. In addition, the type of micro-ball bearing was presented...
to reduce the friction of disc and bearing [15].

Unlike the aforesaid reports (i.e., passive type), an anti-collision control strategy which includes two Look-up tables (i.e., active type) is proposed in this work. In order to prevent the seismic disc from collision with the centre bearing and the EM poles, the anti-collision controller is synthesized and examined by experiments. Two Look-up tables which define the intensity of the applied current to the EM poles are constructed. In addition, the self-sensing technique is included to measure the real-time offset and the precession of the disc by two orthogonal pairs of EM poles, without any additional sensors. The entire anti-collision control loop is intensively inspected and verified under the environment constructed by the interface module dSpace DS1104 and MATLAB Simulink.

2. Problem Statement

A gyroscope is used to detect and measure the exerted angular rate. Hence the detection element, i.e., the seismic disc, has to meet a few requirements such as: 1) reciprocal rotation, clockwise and counter clockwise, at high frequency (e.g., 7000 Hz), 2) able to tilt to respond to the exerted angular excitation, and 3) anti-collision against the electronic or magnetic components. In order to drive the seismic disc into high-frequency resonance, the drive power and switch frequency to alternatively change rotation direction are the key factors for assurance of gyroscope performance. That is, only if the seismic disc is able to rotate at high speed steadily, the detection capability of gyroscope can be outstanding. This is the main goal of this work. Another key issue of this paper is that the tilt motion of the seismic disc has to exhibit large angular displacement without collision. In other words, the seismic disc has to successfully conduct 3-dimensional rotation: spin, yaw and pitch.

As aforesaid, the seismic disc is rotating (C.W. and C.C.W.) about the principal axis, i.e., Z-axis, as shown in Figure 1. That is, the spinning speed, $\dot{\theta}_z$, has to be retained or the function of gyroscope becomes vanished (if spinning speed is zero or varying). If an external angular rate, $\dot{\theta}_x$, was applied on the gyroscope, the seismic disc would respond to tilt about Y-axis, i.e., $\dot{\theta}_y$, would be induced, due to the Coriolis effect. On the other hand, $\dot{\theta}_z$, is induced if external angular excitation, $\dot{\theta}_y$, is exerted, as shown in Figure 1(b).

The seismic disc in our work is driven by side-drive fashion [7]. Totally twelve EM (Electromagnetic) poles are fabricated around the disc, as shown in Figure 2. These EM poles are divided into 4 triplets. Each triple consists of 3 consecutive EM poles and each triplet is driven by 3-phase AC current in shift. That is, the 3-phase AC current is orderly supplied to the 4 triplets of EM poles. In other words, a rotational and alternating magnetic field is constructed by the drive circuit (to be discussed later) to enclose the seismic disc. According to Faraday theorem, two EMFs (Electro-magnetic Forces) are induced between EM poles and the disc made of aluminum. The first kind of EMF is “Motional EMF ($e_r$)”, which generates the tangential attractive force, $F_t$, on the disc. The second kind of EMF is “Transformer EMF ($e_r'$)” which generates the radial repulsive force, $F_r$, on the disc. The tangential force $F_t$ makes the disc.
to rotate but the radial force $\vec{F}_r$ results in further offset and precession of the disc. Since $\vec{F}_r$ and $\vec{F}_s$ are the main exerted forces applying on the seismic disc, they will be numerically evaluated and addressed in next section. In order to account for the offset and precession of the seismic disc due to the radial repulsive force $\vec{F}_r$ and the inherent mass eccentricity, a control strategy for anti-collision on the rotating disc against the centre bearing and the EM poles is proposed and verified in Section 4 and Section 5 respectively.

3. In-Plane Dynamic Model of Disc Position Deviation

Due to imperfect fabrication (e.g., non-uniform thickness) and the asymmetry of mass distribution, the offset of mass center of the rotating disc with respect to the geometric center (i.e., eccentricity) is definitely inevitable in practice. More over, the position of disc in motion is dynamical and tends to cause collision against the adjacent electro-magnetic poles or the centre bearing. In other words, a control loop is necessary to prevent any potential “overshoot” of the position deviation of the rotating disc. For controller synthesis and computer simulation of the disc dynamics, the in-plane mathematic dynamic model is developed at first in this section. The coordinate system of the rotating disc is depicted in Figure 3, where $(\hat{e}_x, \hat{e}_y, \hat{e}_z)$ is the Inertia Frame and “O” the origin. “G” is the mass center of disc. “S” is the geometric center of disc. “e” is the eccentric distance. “r” is the position deviation of the mass center. The major modes of the rotation of disc include spin (i.e., $\dot{\theta}$) and precession (i.e., $\dot{\phi}$). It is noted that the spin motion does not cause collision between the disc and the centre bearing at all. Another planar coordinate, $(x, y)$, is thus defined to describe the linear translation and precession of the disc. By Lagrange’s equation and assumptions: $r \leq 10 \mu m$, $-5^\circ \leq \theta \leq 5^\circ$, (the disc is driven to reciprocally rotate within the angular interval, $-5^\circ \leq \theta \leq 5^\circ$) and $e \approx 25 \mu m$ (i.e., 1% of the radius of disc, which is about 2500 $\mu m$), the in-plane dynamic model of the rotating disc can be accordingly simplified and established:

$$\dot{r} = \frac{1}{m}[me\dot{\theta}^2 + mr\dot{\phi}^2 + me\dot{\phi}\dot{\theta}] - \frac{2eC_\phi}{R^2}\dot{\phi}\dot{\theta} + \frac{2e}{R^2}\theta Q_o - C_r \ddot{r} - K_r r + Q_r]$$ (1)

$$\dot{\theta} = \frac{1}{I_\phi}[me\dot{\phi} + C_\phi \dot{\theta} + Q_o]$$ (2)

Figure 3. Deviation, coordinates and offset of disc

$$\ddot{\phi} = \frac{1}{I_\phi}[-2mr\dot{r}\dot{\phi} - me\dot{\theta} - C_\phi \dot{\phi} + Q_o]$$ (3)

where the drive force ($Q_r$) and drive moments ($Q_\theta$ and $Q_\phi$) are induced by the electromagnets which enclose the disc. Define $(F_{r1}, F_{r2}, F_{r3}, F_{r4})$ and $(F_{s1}, F_{s2}, F_{s3}, F_{s4})$ as the tangential and radial forces generated by the four triplets of 3-phase AC-drive electromagnetic poles. The FBD (Free Body Diagram) of the disc is shown in Figure 4. The geometric relation among $F_{r1}$, $F_{s1}$, $G$, $S$ and $O$ is shown in Figure 5, where $\Gamma_1$, $\alpha_1$, $\beta_1$ and $\gamma_1$ are defined as follows:

$$\Gamma_1 = \pi - (A + \gamma_1) - \theta$$

$$= \pi - \theta - A_1 - \gamma_1 = \frac{\pi}{2} + \phi$$ (4)

$$\alpha_1 = \arcsin\left(\frac{r \cos \phi}{R}\right) = \alpha_3$$ (5)

Since $r \leq 10 \mu m$ and $R = 2500 \mu m$, it leads to

$$\sin\left(\frac{r \cos \phi}{R}\right) \approx \frac{r \cos \phi}{R} \approx 0$$ (6)

That is, $\alpha_1 = \alpha_3 \approx 0$.

$$\beta_1 = \pi - \left(\frac{\pi}{2} - \phi\right) - \alpha_1 = \pi \left(\frac{\pi}{2} + \phi\right) - \alpha_1 = \frac{\pi}{2} + \phi$$ (7)

and

$$\gamma_1 = \pi - \beta_1 - \theta = \frac{\pi}{2} - \phi - \theta + \alpha_1 = \frac{\pi}{2} - \phi - \theta$$ (8)

(0 $^\circ$ $\leq \phi + \theta < 90^\circ$)

The tangential force $F_{r1}$ can be expressed in terms of
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Figure 4. Free body diagram of disc

Figure 5. Geometric relation of tangential force $F_{t1}$ and radial force $F_{r1}$

the drive current frequency, $\omega$, and the position of the disc, ($r$, $\theta$, $\phi$), as follows:

$$F_{t1} = \frac{8(N_S - \phi - \theta)B^2_0D}{\pi D(s_0 + d - r \cos \phi + l_1)\sqrt{R^2 + (\omega L_r)^2}} \cos^2(\omega t - 2\phi - 2\theta)$$

(9)

Similarly,

$$F_{r2} = \frac{8(N_S - \phi - \theta)B^2_0D}{\pi D(s_0 + d + r \cos \phi + l_1)\sqrt{R^2 + (\omega L_r)^2}} \cos^2(\omega t - 2\phi - 2\theta)$$

(10)

$$F_{r3} = \frac{8(N_S - \phi - \theta)B^2_0D}{\pi D(s_0 + d - r \sin \phi + l_1)\sqrt{R^2 + (\omega L_r)^2}} \cos^2(\omega t - 2\phi - 2\theta)$$

(11)

$$F_{r4} = \frac{8(N_S - \phi - \theta)B^2_0D}{\pi D(s_0 + d + r \sin \phi + l_1)\sqrt{R^2 + (\omega L_r)^2}} \cos^2(\omega t - 2\phi - 2\theta)$$

(12)

By the same arguments, the radial magnetic attractive forces can be evaluated by:

$$F_{r1} = \frac{\omega B^2_0 RD}{\pi Rl_1(s_0 + d + l_1 - r \sin \phi)^2 \omega L_r} \sin(2\omega t - 4\phi)$$

(13)

$$F_{r2} = \frac{\omega B^2_0 RD}{\pi Rl_1(s_0 + d + l_1 + r \cos \phi)^2 \omega L_r} \sin(2\omega t - 4\phi)$$

(14)

$$F_{r3} = \frac{\omega B^2_0 RD}{\pi Rl_1(s_0 + d - l_1 + r \sin \phi)^2 \omega L_r} \sin(2\omega t - 4\phi - 4\phi)$$

(15)

$$F_{r4} = \frac{\omega B^2_0 RD}{\pi Rl_1(s_0 + d - l_1 - r \sin \phi)^2 \omega L_r} \sin(2\omega t - 4\phi)$$

(16)

Finally, the drive force ($Q_r$) and drive moments ($Q_\theta$ and $Q_\phi$) can be described by:

$$Q_r = (F_{r1} \cos A_1 \cos G_1 + F_{r2} \cos A_2 \cos G_2)$$

$$+ (F_{r3} \sin A_1 \cos G_1 - F_{r4} \sin A_2 \cos G_2)$$

$$- F_{r3} \sin A_1 \cos G_3 - F_{r4} \sin A_2 \cos G_4$$

$$+ (F_{r1} \sin \phi + F_{r4} \sin \phi) + (F_{r2} \cos \phi - F_{r3} \cos \phi)$$

(17)

$$Q_\theta = F_{r1} R_1 \cos A_1 + F_{r2} R_2 \cos A_2$$

$$+ F_{r3} R_3 \cos A_1 + F_{r4} R_4 \cos A_4$$

$$+ F_{r1} R_1 \sin A_1 + F_{r2} R_2 \sin A_2$$

$$+ F_{r3} R_3 \sin A_1 + F_{r4} R_4 \sin A_4$$

$$= F_{r1} \sqrt{R^2 - 2eR \sin (\phi + \theta)}$$

(18)

$$+ F_{r2} \sqrt{R^2 + 2eR \cos (\phi + \theta)}$$

$$+ F_{r3} \sqrt{R^2 + 2eR \cos (\phi + \theta)}$$

$$+ F_{r4} \sqrt{R^2 - 2eR \sin (\phi + \theta)}$$

$$Q_\phi = F_{r1} R_1 + F_{r2} R_2 + F_{r3} R_3 + F_{r4} R_4$$

$$= (F_{r1} + F_{r2} + F_{r3} + F_{r4})$$

(19)

Based on the dynamic model of the rotation disc, i.e., Equations (1-3) and Equations (17-19), the computer simulations on the disc motion can be undertaken and the control strategies can be therefore developed. They will be addressed in next section.
4. Control Strategy

The control goal of our work is to prevent the rotating disc from collision against the centre bearing so that the electromagnetic poles enclosing the disc can be thus protected. The associate system parameters and their actual values to synthesize the anti-collision controller are listed in Table 1. It is noted that the nominal gap between the disc and the centre bearing cannot be narrowed down much because, as mentioned in Section 2, the disc has to conduct 3-dimensional rotation concurrently.

At first, the open-loop motion of the disc is studied. Once the twelve electromagnetic poles are in-shift energized (i.e., 4 triplets individually and orderly driven by a set of 3-φ AC drive current), the offset of the geometric center, with respect to time, is shown in Figure 6 with absence of any anti-collision controller. Since the nominal gap between disc and the centre bearing is 10 µm, the disc tends to collide with the centre bearing “immediately”. Let the rotation speed of disc be “n” (in RPM) and the initial angle, θ’, defined by $θ = 360° × n + θ’$ $(n \in N)$, $-5° ≤ θ’ ≤ 5°$. Apparently, the collision between disc and the centre bearing would definitely occur, from Figure 7 and Figure 8, if any anti-collision control strategy is not engaged at all.

As a matter of fact, the disc offset, r, which can be measured and obtained by self-sensing technique [16], can be used as the feedback of control loop to prevent collision. That is, once the disc offset, r, grows up to a certain level, then a control strategy has to be activated, e.g., shut-down of the supplied current at the EM pole triplet which the disc is approaching. In our work, two LUTs (Look-up Tables) are therefore constructed for the operation for the applied currents at EM poles to be undertaken. In this paper, 4 sense coils (see Figure 9) are selected to carry high-frequency sinusoidal currents (i.e., measurement current) so that the actuation current (in low-frequency) to EM poles is not affected at all. The

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Physical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Gap between Rotating Disc and EM Poles, d</td>
<td>10 µm</td>
</tr>
<tr>
<td>Skin Depth of Eddy Current, lₑ</td>
<td>5 µm</td>
</tr>
<tr>
<td>Equivalent Path Length w.r.t. the Center of EM Pole, s₀</td>
<td>100 µm</td>
</tr>
<tr>
<td>Permeability in Air, μ₀</td>
<td>$4π × 10^{-7}$ H/m</td>
</tr>
<tr>
<td>Number of the Windings, N</td>
<td>15 turns</td>
</tr>
<tr>
<td>Thickness of Rotating Disc, D</td>
<td>250 µm</td>
</tr>
<tr>
<td>Radius of Rotating Disc, R</td>
<td>2500 µm</td>
</tr>
<tr>
<td>Eccentric Distance, e</td>
<td>25 µm</td>
</tr>
<tr>
<td>Angular Moment of Inertia w.r.t. G, Iₒ</td>
<td>$4.142 × 10^{11}$ Kg.m²</td>
</tr>
<tr>
<td>Frequency of the AC Current, fₒ = ω/2π</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Amplitude of the AC Current, Iₒ</td>
<td>100 mA</td>
</tr>
</tbody>
</table>

Figure 6. Offset of the geometric center of disc W/O control loop

Figure 7. Collision between disc and centre bearing under various initial angles

Figure 8. Collision between disc and centre bearing under various spin speeds ($θ’=0°$)

self-sensing technique can be referred to our previous work in [16]. For simplicity, denote the EM poles, (A1,
B1, C1), as Triplet #1, as shown in Figure 9. Similarly, denote (A2, B2, C2), (A3, B3, C3) and (A4, B4, C4) as Triplet #2, Triplet #3 and Triplet #4 respectively. For each triplet, the pole-to-pole phase shift is 120°. The supplied current to the 4 triplets are: \( I_1 + I_m \), \( I_2 + I_m \), \( I_3 + I_m \) and \( I_4 + I_m \) orderly, where \( I_1 \), \( I_2 \), \( I_3 \) and \( I_4 \) are defined as follows:

\[
\begin{align*}
I_1 &= W_1 W_K I_m \\
I_2 &= W_2 W_K I_m \\
I_3 &= W_3 W_K I_m \\
I_4 &= W_4 W_K I_m
\end{align*}
\]  

\( W_1 \), \( W_2 \), \( W_3 \) and \( W_4 \) are the weights on applied currents and listed in Table 2, referred as LUT1 (Look-up Table #1). \( W_K \) is also a weighting factor, whose physical values for various conditions are listed in Table 3, referred as LUT2 (Look-up Table #2). LUT1 is constructed, on the basis of precession angle and the disc offset, \( r \). On the contrary, LUT2 is constructed, on the basis of measured spinning speed, \( \theta \), and initial spin angle, \( \theta^* \). It is noted that the Interpolation and Extrapolation approaches are employed to calculate \( W_1 \), \( W_2 \), \( W_3 \), \( W_4 \) and \( W_K \) for real-time measurements and estimation on \( (r, \varphi, \theta \) and \( \dot{\theta} \).

An illustrative example is shown in Figure 10. The initial conditions are: offset \( r_o = 8 \mu m \), initial angle of the mass center, \( \theta^* = 0^\circ \) and the spinning speed, \( \dot{\theta} = 30 \text{ k RPM} \). It is observed that the overshoot of the disc offset is about 6% but successfully suppressed within 0.4 \( \mu m \). That is, the rotating disc can be controlled to move within a circular region which allows about 8 \( \mu m \) offset for maximum. On the other hand, the collision between disc and the centre bearing or disc and electromagnetic poles is completely prevented.

### 5. Drive Circuit for Electromagnetic Poles

The goal of the drive circuit is to make the disc be able to reciprocally rotate within \( \pm 5^\circ \) clockwise and counterclockwise smoothly and switch direction at high-frequency. The drive frequency of the circuit is expected to be identical to the natural frequency of the drive mode of the micro-gyroscope so that expected resonance can be ensured. Normally, it is about 7000 Hz or above. The drive circuit is composed of 3 portions: power supply module, inverter and the sequential drive control by the MPU (Micro-Processor Unit), shown in Figure 11. The power supply module mainly consists of the rectifier, LPF (Low Pass Filter) and the voltage regulator in which differential operation amplifier, OP1, is embedded. The output of the power supply module is a DC voltage which is the input of the inverter, as shown in Figure 12.

This voltage can be evaluated by:

\[
V_{PS} = \frac{R_1 + R_2 + R_w}{R_3 + R_{w2}} V_S
\]

where \( V_S \) is the DC voltage after rectifier in the 3-\( \varphi \) AC power supply module. \( R_1 \) and \( R_2 \) are the bias resistances of operation amplifier, OP1. \( R_w \) is variable and controlled by the MPU to tune the magnitude of \( V_{PS} \). \( R_{w2} \) is the partial resistance of \( R_w \).

### Table 2. Weights of anti-collision controller based on precession angle and disc offset (LUT 1)

<table>
<thead>
<tr>
<th>( r(\mu m) )</th>
<th>( \theta^* )</th>
<th>0°</th>
<th>90°</th>
<th>180°</th>
<th>270°</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>W_1 = 0.4</td>
<td>W_1 = 0.4</td>
<td>W_1 = 0</td>
<td>W_1 = 0</td>
<td></td>
</tr>
<tr>
<td>\quad W_2 = 0</td>
<td>W_2 = 0.4</td>
<td>W_2 = 0.4</td>
<td>W_2 = 0.4</td>
<td>W_2 = 0.4</td>
<td></td>
</tr>
<tr>
<td>\quad W_3 = 0</td>
<td>W_3 = 0.4</td>
<td>W_3 = 0.4</td>
<td>W_3 = 0.4</td>
<td>W_3 = 0.4</td>
<td></td>
</tr>
<tr>
<td>\quad W_4 = 0</td>
<td>W_4 = 0.4</td>
<td>W_4 = 0.4</td>
<td>W_4 = 0.4</td>
<td>W_4 = 0.4</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Weights of anti-collision controller based on spin speed and initial spin angle (LUT 2)

<table>
<thead>
<tr>
<th>( \theta^* )</th>
<th>6000</th>
<th>12000</th>
<th>18000</th>
<th>24000</th>
<th>30000</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>W_1 = 0.86</td>
<td>W_2 = 0.89</td>
<td>W_3 = 0.89</td>
<td>W_4 = 0.98</td>
<td>W_5 = 1.06</td>
</tr>
<tr>
<td>4°</td>
<td>W_1 = 0.76</td>
<td>W_2 = 0.79</td>
<td>W_3 = 0.79</td>
<td>W_4 = 0.88</td>
<td>W_5 = 0.96</td>
</tr>
<tr>
<td>3°</td>
<td>W_1 = 0.68</td>
<td>W_2 = 0.71</td>
<td>W_3 = 0.71</td>
<td>W_4 = 0.80</td>
<td>W_5 = 0.88</td>
</tr>
<tr>
<td>2°</td>
<td>W_1 = 0.61</td>
<td>W_2 = 0.64</td>
<td>W_3 = 0.64</td>
<td>W_4 = 0.73</td>
<td>W_5 = 0.81</td>
</tr>
<tr>
<td>1°</td>
<td>W_1 = 0.55</td>
<td>W_2 = 0.58</td>
<td>W_3 = 0.58</td>
<td>W_4 = 0.67</td>
<td>W_5 = 0.75</td>
</tr>
</tbody>
</table>
| 0°            | W_1 = 0.5  | W_2 = 0.53 | W_3 = 0.53 | W_4 = 0.62 | W_5 = 0.7 

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The role of Inverter module, shown in Figure 13(a), is to generate SPWM (Sinusoidal Pulse Width Modulation) signals, in cooperation with MPU which provides the command signal. The six MOSFETs, S1–S6, are sequentially switched on/off by the Inverter module. In order to protect MOSFETs from back current, a feedback diode and a set of snubber circuit, show in Figure 13(b), are included. $V_{TH}$ and $f_C$ denote the magnitude and frequency of the triangle voltage respectively. $V_{A\bar{n}}$, $V_{B\bar{n}}$, and $V_{C\bar{n}}$ are the applied voltages on Poles A, B and C respectively, with respect to the neutral common “n”, as shown in Figure 13. The phase lag between any two adjacent poles is always retained to be 120°. It is also noticed that the drive frequency and the direction of disc rotation are both controlled by MPU since it can control the order and timing of MOSFETs to be switched on.

Before implementation of the drive circuit, the commercial software, OrCAD 9, is employed to verify the function of the proposed circuit. The resulted voltage output generated by the proposed drive circuit is shown in Figure 14. It is observed that the applied voltages at each triplet of electromagnetic poles are really of sinusoidal waves which are pretty smooth and all pole-to-pole delay is in phase shift, 120°, orderly.

### 6. Experimental Results

The actual drive circuit is practically completed and verified under the interface environment constructed by dSPACE DS1104 and MATLAB simulink. The successfully fabricated electromagnetic poles are shown in Figure 15. To examine the efficacy of the control strategy, a test rig, shown in Figure 16, is set up. The control command is provided by MPU for signal trigger. On the other hand, the 3-phase AC power source with peak-to-peak 20.4 Volts is generated by the power supply module, whose photo is shown in Figure 17(a). The photo of inverter module is shown in Figure 17(b). The test points, TP1, TP2 and TP3, are inspected by the scope and shown in Figure 18 and Figure 19. From Figure 18 and Figure 19, the potential noise is almost suppressed by the aforesaid LPF in last section. Therefore, the expected motion of the disk can be ensured even if any disturbance or noise is present. From Figure 19, it can be verified that the output voltage of the drive circuit, i.e., the drain...
Figure 13. Inverter module of the SPWM

Figure 14. Voltage output generated by the drive circuit

Figure 15. Optical microscope (OM) image of electromagnetic poles

Figure 16. Test rig to examine anti-collision strategy

Figure 17. Photo of partial drive circuit

Figure 18. Voltage of test points TP1 (CH1) and TP2 (CH2)

Figure 19. Command voltage at S1 (CH2) and drain voltage VD (CH1)
voltage of the MOSFET, can be successfully controlled by the given command at S1. This implies that the stability and spinning rate of the disk can be considerably assured. Based on the experimental results, the control force and moment, provided by the electromagnetic poles, can be precisely implemented by the proposed control strategy.

7. Conclusions

An innovative drive circuit, in cooperation with a MSU (Micro-Processor Unit), is proposed and verified by experiments to efficiently generate adequate drive power to make the seismic disc oscillate under SPWM (Sinusoidal Pulse Width Modulation) operation. On the other hand, the rotating disc is designed to concurrently conduct three modes of motion: spinning, precession and translation (i.e., offset). That is, the position deviation of the disc has to be regulated or the collision between disc and the centre bearing would occur. An anti-collision controller based on two LUTs (Look-up Tables) to tune the amplitude of applied current to the EMs (Electromagnetic Poles) is presented and examined. On the actuation aspect, the efficacy of drive manner by VVVF (Variable Voltage Variable Frequency) is verified by both computer simulations and experiments. For the sensor aspect, two orthogonal pairs of EM pairs are used as the disc position measurement units. That is, the self-sensing technique has been employed in this work.

Though the drive power by the proposed drive circuit is sufficient to make the disc rotate at high frequency, the sensitivity of frequency mismatch (i.e., the impact on desired resonance) should also be evaluated. The anti-collision strategy is, as a matter of fact, to reduce the amplitude of supplied current to the EM poles as the position deviation of disc exceeds the preset upper limit. This implies that the amplitude of the effect of resonance is reduced as well and hence the performance (e.g., resolution) is, to some extent, degraded. These two issues will be investigated in the near future.

8. Acknowledgements

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Measurement and Analysis of Temperature Dependent Resistance of La$_{0.67}$Sr/Ca$_{0.33}$MnO$_3$ CMR Samples Using LabVIEW

Sunita Keshri$^1$, Leena Joshi$^1$, Sanat Kumar Mukherjee$^1$, Vyacheslav Fedorovich Kraidenov$^2$

$^1$Department of Applied Physics, Birla Institute of Technology, Mesra, India; $^2$Institute of High Pressure Physics of the Russian Academy of Sciences, Troitsk, Russia.

Email: s_keshri@bitmesra.ac.in, ss_keshri@rediffmail.com

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ABSTRACT

In this paper we report design of one virtual instrument for the measurement of resistance as a function of temperature. The program has been developed using the National Instruments’ graphical programming language ‘LabVIEW’ and has been run for the measurement of magnetoresistance of some colossal magnetoresistive (CMR) compounds, La$_{0.67}$Ca/Sr$_{0.33}$MnO$_3$.

Keywords: CMR, Manganites, Magneto-Transport Properties, LabVIEW Program, Virtual Instrument

1. Introduction

LabVIEW [1] is graphical programming software developed by National Instruments. Using LabVIEW, ready-made virtual instrument (VI) can be developed for various applications. It is a graphical programming language and hence all programming is made with blocks representing functions, icons representing variables and lines representing path of the variables [2]. The LabVIEW graphical development environment creates flexible and scalable design, control, and test applications. With LabVIEW, one can interface several equipments with computer together for precise measurements, analyze data for meaningful information and share results through intuitive displays. Many exciting experiments can be designed and demonstrated by integrating these VI technology products in a flexible laboratory environment with enormous possibilities of expansion and experimentation. Aim of our present instrumentation was to design programs for the measurement of resistance with the variation of temperature.

In this paper we report the magneto-transport behaviors of some colossal magnetoresistive (CMR) compound [3,4] using the above-said instruments coupled by VI designed using LabVIEW program. These materials have been widely studied because of their potential applications [3,4] and interesting properties like metal-insulator (M-I) transition, paramagnetic-ferromagnetic (PM-FM) transition, large negative magnetoresistance (MR) over a wide temperature range, spin polarization etc. It has been recognized that the CMR effect typically exhibits in the vicinity of M-I transition temperature accompanied by a simultaneous paramagnetic to ferromagnetic transition at the Curie temperature [5,6]. For the present work, La$_{0.67}$Sr/Ca$_{0.33}$MnO$_3$ (LSMO/LCMO) have been synthesized and characterized for structural and magneto-resistive behaviors.

2. Experimental

Polycrystalline samples of LSMO and LCMO were prepared by the conventional solid state route. The stoichiometric amount of La$_2$O$_3$, Sr/CaCO$_3$ and (CH$_3$COO)$_2$Mn.4H$_2$O were taken. The powdered samples were first sintered at 900°C for 24 hrs and then at 1100°C for 18 hrs with intermediate grindings. The powder thus obtained was pelletized and annealed at 1250°C for 12 hrs with intermediate grinding and repelletization and finally furnace cooled to room temperature. Structural properties of these prepared samples have been found to be similar with previous results [7,8].

For the measurement of resistivity, the prepared pellet was cut into rectangular shape. Four thin copper wires, attached to the sample by means of conducting silver epoxies, act as current and voltage leads. Current was supplied through the outer two leads and inner two were...
used for sensing developed voltage using sourcemeter (Keithley 2400), as shown in Figure 1. The sample was arranged inside a closed cycle He-cryostat (Oxford Instruments), controlled by ITC temperature controller (Oxford Instruments 503S). An electromagnet was placed across the sample as shown in the same figure. We have measured the dc electrical resistivity of the samples for the temperature range 10 to 300 K, with zero and 1 T applied magnetic field.

3. LabVIEW Application

LabVIEW is a graphical programming consisting of three important components involved in the test and measurement applications, namely 1) Data acquisition, 2) Data analysis, and 3) Data visualization.

Figure 2 represents the front panel of the VI developed for four probe resistivity measurement. The VI draws data from parallel running temperature controller and sourcemeter and feed it into the computer through RS232 cables. The right part of the front panel is designed for visualization of input and output data and left part is made to visualize the plot corresponding to output (resistance versus temperature) data. The input data required to run the VI consists of path of the file (txt format) where data are to be stored, the value of compliance, temperature interval required, next temperature and the current supplied, as shown in the right upper part. The output data comprise of output voltage, estimated resistance of the sample and the standard deviation associated with the measurement. Using this VI we take data for either of heating or cooling cycles as shown in the right lower part of the front panel.

The corresponding circuit diagrams of three important parts of the same VI are shown in Figures 3(a)-3(c). Figure 3(a) shows the block for configuring the sourcemeter at the parameters defined by the user. “Configure” button sets the sourcemeter to the given condition and “Measure” button makes it ready for measuring the voltage developed. The program offers the flexibility to set input current value and compliance limit suitable for the sample under test. Figure 3(b) is the block diagram for four probe resistance measurement. Voltage is recorded by reversing the polarity of the current. This eliminates the instrumental error. Figure 3(c) is the temperature recording block. It senses the temperature and according to the given interval when the temperature controller attains the next temperature, the data is displayed and stored. The value of the temperature interval is to be added or subtracted to the present temperature value corresponding to heating and cooling cycles respectively. For both the cycles, data can be stored in a fixed temperature interval. VI can set the minimum interval of 0.1 K during heating as well as cooling cycles.

4. Results and Discussions

Figure 4 demonstrates the temperature dependent resistance of the samples measured using the above said VI in presence of magnetic field of strength 0 and 1 Tesla. In absence of magnetic field, both the samples LSMO and LCMO show broad humps corresponding to M-I transitions at temperatures 273.0 K and 201.6 K respectively. With the application of 1 Tesla magnetic field, resistivity of both the samples decreases whereas M-I transition temperature increases towards higher values 280.5 K and 203.2 K respectively, as also reported by many other researchers [9-12]. MR is defined as \[ \frac{\rho(T, 0) - \rho(T, H)}{\rho(T, 0)} \times 100 \% \], where \( \rho(T, 0) \) and \( \rho(T, H) \) is resistivity values in zero and applied fields respectively. MR as a function of temperature measured in the presence of 1 T magnetic field is presented for both the samples in Figures 5(a)-(b). The nature of temperature dependent MR plot is in agreement with some previous reports [9,12].
In one of the previous reports [13] we find that the data of such samples can be fitted well assuming random network of resistances with two types of resistivities. According to them, the $\rho(T)$ data can be analysed assuming random network of resistances with two types of resistivities—one more resistive ($\rho_1$) than the other ($\rho_2$) as considered by Rao et al. [13]. These two resistivities, $\rho_1$ [14] and $\rho_2$ [15], are temperature dependent but independent of each other. Total resistivity $\rho(T)$ can be expressed as:

$$\rho(T) = 4\rho_1\rho_2 / [(3f - 1)\rho_1 + (2 - 3f)\rho_2] + \{(3f - 1)\rho_1 + (2 - 3f)\rho_2\}^2 + 8\rho_1\rho_2 f^{1/2}$$

(1)

For these samples as the broad hump observed in $\rho(T)$ is due to a bond percolation because of the broken Mn-O-Mn linkage, it could be well described by a temperature independent metallic volume fraction ($f$). The corresponding best fit line is shown by red colour in Figures 4(a)-(b). It is observed that the metallic behavior dominates in the lower temperature region whereas the insulating behavior, in the higher temperature region. A crossover is occurred at an intermediate temperature resulting in a M-I transition.

5. Conclusions

The authors have designed VI for measuring temperature

Figure 4. Resistivity and MR as a function of temperature at 0 and 1 T applied field. Solid symbols represent the data points while best fitted curves using “(1)” are shown by red colour
dependent resistance using LabVIEW program. In order to verify the measured data of some standard CMR samples using this VI, a systematic study of electrical resistivity of LCMO and LSMO was undertaken as a function of temperature (10–300 K) and in presence of magnetic field of strength 0 T and 1 T. The results obtained by the VI are satisfactory. Such automation allows the users to run the tests without human assistance and includes high efficiency since human errors are avoided and repeatability is more easily achieved.

6. Acknowledgements

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REFERENCES

Effect of Zn Substitution on the Magnetic Properties of Cobalt Ferrite Nano Particles Prepared Via Sol-Gel Route

Sonal Singhal1*, Tsering Namgyal1, Sandeep Bansal2, Kailash Chandra3

1Department of Chemistry, Panjab University, Chandigarh, India; 2Department of Metallurgical and Materials Engineering, Indian Institute of Technology-Roorkee, Roorkee, India; 3Institute Instrumentation Centre, Indian Institute of Technology-Roorkee, Roorkee, India.
Email: sonal1174@gmail.com
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ABSTRACT
Zinc substituted cobalt ferrite nanoparticles (Co0.5Zn0.5Fe2O4 with x = 0.0, 0.2, 0.4, 0.8 and 1.0) were prepared via sol-gel route and the effect of zinc concentration on saturation magnetization and lattice parameter were investigated. The particle sizes of the as obtained samples were found to be ~10 nm which increases upto ~92 nm on annealing at 1000°C. The frequency bands near 564-588 cm⁻¹ and 425-442 cm⁻¹ are assigned to the tetrahedral and octahedral clusters which confirm the presence of M-O stretching band in ferrites. The unit cell parameter ‘a’ increases linearly with increasing concentration of zinc due to larger ionic radii of Zn²⁺ ion. It was found that this substitution allows tunable changes in the magnetic properties of cobalt ferrite. Interestingly, saturation magnetization first increases upto x = 0.4 and then decreases for higher Zn substitution, thus tunable changes in magnetic properties of cobalt ferrite are possible. Source of such behaviour could be the variation of exchange interaction between the tetrahedral and the octahedral sites.

Keywords: Nano Particles, Saturation Magnetization, Coercivity, X-Ray Diffraction

1. Introduction
Nanocrystalline ferrites are currently the subject of interest because of its wide application in industrial as well as research areas. They are attractive because of their importance in ferrofluids, magnetic drug delivery, hyperthermia for cancer treatment, etc. [1]. An interesting example is that of CoFe2O4 which has got some peculiar properties like high saturation magnetization (Ms), high coercivity (Hc) and large anisotropy [2]. Further the substitution of Co²⁺ in this ferrite with Zn²⁺, Ni²⁺, Cu²⁺ etc. allows some tunable changes in its properties.

CoFe₂O₄ has inverse spinel structure with Co²⁺ ions in octahedral sites and Fe³⁺ ions equally distributed between tetrahedral and octahedral sites whereas ZnFe₂O₄ has a normal spinel structure with Zn²⁺ ions in tetrahedral and Fe³⁺ in octahedral sites [3]. Therefore, Zn-substitution in CoFe₂O₄ may have some distorted spinel structures depending upon the concentration of the precursor solutions. Effect of laser irradiation on the cation distribution mechanism of Co0.5Zn0.5Fe2O4 ferrite was explained by Tawfik et al. [4]. It is observed that a displacement of Fe³⁺ ions from its original positions alters the Fe³⁺-O²⁻ bond lengths which change the IR absorption bands. Dey and Ghose prepared Co0.5Zn0.5Fe2O₄ by co-precipitation method and found decrease in magnetization with increasing particle size [5]. Arulmurugan et al. [6] suggested that substitution of Co²⁺ with Zn²⁺ lead to improved magnetic properties of nanocrystalline ferrites. They also observed a decreasing behavior of saturation magnetization and the particle size of the Co-Zn substituted ferrite nanoparticles with increasing Zn concentration.

Islam et al. [7] reported that saturation magnetization decreases with zinc concentration in cobalt zinc ferrites prepared by ceramic technique. Vaidyanathan et al. [8] also reported decrease in magnetic properties such as Ms, Hs, Hc, and Mh with increase in zinc substitution. Single phase and monodispersed nanocrystalline Zn-substituted Cobalt ferrites with grain size of 3 nm were prepared by Duong et al. [9] using forced hydrolysis method and found that the ferrites were super paramagnetic at room temperature and ferrimagnetic at lower temperatures. Recently Waje et al. [10] reported that Co0.5Zn0.5Fe2O₄ nanoparticles, prepared by mechanical alloying and sintering show a constant value of permittivity within
a measured frequency range but vary with sintering temperature. However, in general the permeability values vary with both frequency and sintering temperature.

The present work deals with the synthesis of nano particles of zinc substituted cobalt ferrite (Co$_x$Zn$_{1-x}$Fe$_2$O$_4$ where $x = 0, 0.2, 0.4, 0.6, 0.8, \text{ and } 1.0$) via sol-gel method and characterized using infrared spectroscopy (IR), transmission electron microscope (TEM), X-ray diffractometry (XRD) and magnetic measurements. Studies were also carried out after annealing the sample at various temperatures to see the effect of particle size on different properties. This work is an attempt to investigate the magnetic properties of zinc substituted cobalt ferrites.

2. Experimental

2.1 Preparation of Ferrites

Nanoparticles of zinc substituted cobalt ferrites Co$_x$Zn$_{1-x}$Fe$_2$O$_4$ (where $x = 0.0, 0.2, 0.4, 0.6, 0.8$ and $1.0$) were prepared using sol-gel method (Figure 1). In this method each sample was prepared by taking the desired proportion of precursor nitrates, i.e., cobalt nitrate, iron nitrate and zinc nitrate were separately dissolved in minimum amount of water. After heating them at 80-90°C all the solutions were mixed. The solution thus obtained was stirred for sometimes and then citric acid followed by ethylene glycol was added. The solution was again stirred till gel formation. This gel self ignites and results in nano particles of desired ferrite. These samples were then annealed at different temperatures for further characterization.

2.2 Physical Measurements

The infrared spectra of all the samples were recorded in the range 4000-400 cm$^{-1}$ in FTIR instrument (PERKIN ELMER) using KBr pellets. The elemental analysis were carried out by two methods viz. Electron probe micro analyzer (EPMA) (JEOL, 8600 M) and Atomic Absorption Spectrometer (AAS) (GBC, Avanta). In EPMA about 2 mm thick pellets were prepared, fixed on the sample holder and coated with the carbon to make them conducting. Analysis was done after calibrating the instrument with internal standards. Similarly analysis on AAS was also performed after calibrating the instrument with at least three standards elemental concentration. The results from two instruments were consistent and very close to the formula of the ferrite. The X-ray diffraction studies were carried out on X-ray diffractometer (Bruker AXS, D8 Advance) with FeK$_\alpha$ radiation. Finally the magnetic measurements were made on a vibrating sample magnetometer (VSM) (PAR-155).

3. Results and Discussions

3.1 FT-IR Characterization

In the FT-IR spectra the frequency bands near 564-588 cm$^{-1}$ and 425-442 cm$^{-1}$ are assigned to the tetrahedral and octahedral clusters and confirms the presence of M-O stretching band in ferrites as suggested by Pradeep and Chandrasekaran [11]. The authors suggested that the vibrational mode of tetrahedral clusters is higher as compared to that of octahedral clusters, which is attributed to the shorter bond length of tetrahedral clusters.

3.2 X-Ray Diffraction Studies

Typical X-Ray diffraction pattern for the sample Co$_{0.6}$Zn$_{0.4}$Fe$_2$O$_4$ after annealing at 400, 600, 800, 1000°C are shown in Figure 2. The diffraction pattern did not show any peaks for the as prepared ferrite samples thereby showing the amorphous nature of the samples. However for the annealed samples regular peaks were observed, which confirmed that particle size increases with increase in temperature and the intensity of the peaks grew stronger with the grain size growth. The samples were found to be face centered cubic with Fd-3m space group.

Figure 3 represents the X-Ray powder diffraction pattern for the samples Co$_x$Zn$_{1-x}$Fe$_2$O$_4$ (where $x = 0.0, 0.2, 0.4, 0.6, 0.8$ and $1.0$) annealed at 1000°C. The lattice parameters were calculated using Powley and Le-Bail refinement methods. It is observed that the lattice parameter 'a' increases linearly with increase in zinc concentration as shown in Figure 4. The reason for this increase of lattice parameter values may be due to the larger ionic radii of Zn$^{2+}$ (88 pm) as compared to Co$^{3+}$ (83.8 pm). The crystallite size was calculated using Debye Scherrer equation [12].

$$d = \frac{0.9 \lambda}{(w-w) \cos \theta}$$

where $d$ is the grain diameter, $w$ is the half intensity.
Effect of Zn Substitution on the Magnetic Properties of Cobalt Ferrite Nano Particles Prepared Via Sol-Gel Route

Figure 2. X-ray diffractographs of \( \text{Co}_{0.6}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4 \) (a) as obtained and after annealing at (b) 400; (c) 600; (d) 800 and (e) 1000°C

Figure 3. X-ray diffractographs of \( \text{Co}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4 \) after annealing at 1000°C
where MBCo0.6Zn0.4Fe2O4, the saturation magnetization increases in the sublattice MA, resulting in the increase of total magnetic A-sites, causing the decrease of magnetic moment in the zero magnetic moment) replace ion on the tetrahedral lattice at 1000 oC.

Annealing at 1000 oC are also shown in Figure 5. Typical hysteresis loops for the samples Co0.2Zn0.8Fe2O4, Co0.4Zn0.6Fe2O4, Co0.8Zn0.2Fe2O4 are also shown in Figure 6. The hysteresis loop for the as obtained sample exhibits no hysteresis, which may be attributed to superparamagnetic relaxation. The saturation magnetization of the annealed samples of CoFe2O4 at 1000°C is ~84 emu/g, which is in good agreement with the reported values [13,14].

In a cubic system of ferromagnetic spinels, the magnetic order is mainly due to a super exchange interaction mechanism occurring between the metal ion in the A and B sublattices. The substitution of nonmagnetic ion such as zinc, which has a preferentially A site occupancy results in the reduction of the exchange interaction between A and B sites. Hence, by varying the amount of zinc substitution, it should possible to vary magnetic properties of the samples. According to Neel’s two sublattice model of ferrimagnetism, the magnetic moment per formula unit in μB, nB(x) is expressed as:

\[ n_B(x) = M_B(x) - M_A(x) \]

where M_B and M_A are the B- and A-sublattice magnetic moment in μB respectively.

The saturation magnetization for all the ferrites after annealing at 1000°C is listed in Table 1. From the Table 1 it is clear that for the samples CoFe2O4, Co0.2Zn0.8Fe2O4, and Co0.6Zn0.4Fe2O4, the saturation magnetization increases from 84.5-91.6 emu/g. This could be due to Zn2+ (with zero magnetic moment) replace ion on the tetrahedral A-sites, causing the decrease of magnetic moment in the sublattice MA, resulting in the increase of total magnetic moment as discussed earlier. On further increase of zinc substitution in Co0.2Zn0.8Fe2O4, Co0.6Zn0.4Fe2O4 and ZnFe2O4 the saturation magnetization decreases. This could be due to further increase in the concentration of Zn2+ (more than 0.4), the exchange interaction between A and B sites gets lowered resulting in strengthening of B-B interaction and weakening of A-B interaction, which leads to decrease of saturation magnetization.

The value of coercivity (H_C), reaches a maximum value and then decreases as the grain size increases as shown in Figure 5. This variation of Hc with grain size can be explained on the basis of domain structure, critical diameter and the anisotropy of the crystal [15,16]. In the single domain region as the grain size decreases the coercivity decreases because of the thermal effects. The coercivity Hc in the single domain region is expressed as 

\[ H_c = g - h/D^2 \]

where g and h are constants. In the multi domain region the variation of coercivity with grain size increases as the particle diameter increases. A decrease in coercivity as observe in Figure 6, with increase in zinc concentration may be attributed to the decrease in anisotropy field, which in turn decreases the domain wall energy [18,19].

Table 1. Lattice parameters derived from X-ray diffraction pattern and saturation magnetization of the ferrites after annealing at 1000°C

<table>
<thead>
<tr>
<th>Ferrite composition</th>
<th>Lattice parameter (a) (Å)</th>
<th>Volume ((Å^3))</th>
<th>X-ray density ((g/cm^3))</th>
<th>Saturation magnetization ((emu/g))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoFe2O4</td>
<td>8.3834</td>
<td>589.19</td>
<td>5.2962</td>
<td>84.5</td>
</tr>
<tr>
<td>Co0.2Zn0.8Fe2O4</td>
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<td>593.61</td>
<td>5.3159</td>
<td>91.6</td>
</tr>
<tr>
<td>Co0.6Zn0.4Fe2O4</td>
<td>8.4156</td>
<td>596.01</td>
<td>5.3239</td>
<td>54.4</td>
</tr>
<tr>
<td>Co0.8Zn0.2Fe2O4</td>
<td>8.4213</td>
<td>597.22</td>
<td>5.3425</td>
<td>39.3</td>
</tr>
<tr>
<td>ZnFe2O4</td>
<td>8.4322</td>
<td>599.54</td>
<td>5.3511</td>
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</tr>
</tbody>
</table>

Figure 4. Variation of lattice parameters and density with the zinc concentration
4. Conclusions

Sol-gel method has been used to synthesize Zn substituted cobalt ferrite samples at nanometer scale. A slight change in the concentration of the nitrate precursor salts changes the lattice parameter and magnetic properties. The vibrational mode of tetrahedral clusters (564-588 cm\(^{-1}\)) is higher as compared to that of octahedral clusters (425-442 cm\(^{-1}\)), which is attributed to the shorter bond lengths of tetrahedral clusters. An increasing growth of grain size is also observed with increasing annealing temperature and formation of sharp peaks at 1000°C in X-ray powder diffraction pattern is in conformity with this result. The lattice parameter and the X-ray density, increases with increasing Zn concentration. The saturation magnetization first increases from CoFe\(_2\)O\(_4\) to Co\(_{0.6}\)Zn\(_{0.4}\)Fe\(_2\)O\(_4\) and then shows a decreasing behavior till ZnFe\(_2\)O\(_4\).

REFERENCES


Far Infrared Ray Radiation Inhibits the Proliferation of A549, HSC3 and Sa3 Cancer Cells through Enhancing the Expression of ATF3 Gene

Kikuji Yamashita¹, Shine-Od Dalkhsuren¹, Tatsuo Ishikawa¹, Kaori Sumida¹, Jun Ishibashi¹, Hiroyoshi Hosokawa², Akemichi Ueno³, Fumio Nasu⁴, Seiichiro Kitamura¹

¹Department of Oral and Maxillofacial Anatomy, University of Tokushima, Tokushima, Japan; ²Oral and Maxillofacial Surgery, Medical Science for Oral and Maxillofacial Regeneration, Graduate School of Health Biosciences, University of Tokushima, Tokushima, Japan; ³Department of Hygiene Chemistry, School of Pharmaceutical Science, Ohu University, Ohu, Japan, ⁴Department of Anatomy, Faculty of Acupuncture and Moxibustion, Suzuka University of Medical Science, Suzuka, Japan.

Email: kikuji@dent.tokushima-u.ac.jp

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ABSTRACT

Far-infrared ray (FIR) is electromagnetic wave between 4 and 1000 μm. FIR causes heating, but how it affects cells is not well understood. In this study, we developed a culture incubator that can continuously irradiate cells with FIR and examined the effects of FIR on five human cancer cell lines, namely A431 (vulva), A549 (lung), HSC3 (tongue), MCF7 (breast) and Sa3 (gingiva). We found that FIR inhibits cell proliferation and induces cell hypertrophy without apoptosis in A549, HSC3 and Sa3 cells. Flow cytometry revealed that the inhibition of proliferation was due to G2/M arrest. Contrary, FIR did not inhibit cell proliferation and cause cell hypertrophy in A431 or MCF7 cells. Microarray analysis revealed that FIR suppressed the expression of cell proliferation-related and stress-responsive genes in FIR-sensitive cell lines (A549, HSC3 and Sa3). ATF3 in particular was identified as a key mediator of the FIR effect. Over-expression of ATF3 inhibited cell proliferation and knockdown of ATF3 mRNA using an antisense oligonucleotide suppressed FIR-induced growth arrest. These results indicate that a body temperature range of FIR radiation suppresses the proliferation of A549, HSC3, Sa3 cells and it appears that ATF3 play important roles in this effect.

Keywords: Far-Infrared Radiation, Human Cancer Cell Lines, G2/M Arrest, Hypertrophy, ATF3

1. Introduction

Far-infrared ray (FIR), which causes heating, includes electromagnetic waves with wavelengths between 4 and 1000 μm. Recently, there have been many studies of the effects of FIR on health and in the preservation of food. The available evidence indicates that whole-body irradiation by FIR has many biological effects. For example, hyperthermia (body temperature of 39°C to 41°C) induced by whole-body FIR has been reported to substantially inhibit spontaneous mammary tumor growth in mice [1-4]. At normal temperature ranges (approximately 25.5°C) tumor growth in SHN mice can be inhibited by FIR [5,6]. Furthermore, whole-body FIR irradiation is believed to improve human health and sleep by enhancing blood circulation in the skin [7,8]. This is likely due to the ability of organic matter to absorb FIR at wavelengths between 7 to 12 μm.

The effects of FIR and particularly whole-body FIR remain unclear, because the experiments are easily affected by environmental changes in temperature and humidity, by the presence of bacteria, fungi and so on. Therefore, we developed a chamber for raising animals that emits FIR upon heating and is capable of maintaining steady conditions. This system employs a sealed heater with a carbon/silica/aluminum oxide/titanium oxide ceramic coating produced using a polycarbonate printing technique [9]. Using this system, we found that FIR inhibits tumor growth in the A431 tumorigenesis model mouse by inhibiting the expression of matrix metalloprotease-1, 9, 10 and 13. Recent studies by Teraoka et al., found that FIR at wavelengths between 4 to 16 μm inhibits the growth of HeLa cells in vitro at 37°C [10]. Despite these findings, the molecular mechanism by which FIR affects cellular gene expression remains unclear.

The lack of data on the effects of FIR on cells is due to the difficulty in stably irradiating cells with FIR under ideal culture conditions (i.e., 100% humidity, 37.0 ±
0.5°C, 5% CO₂) and examining the effects of FIR at the cellular level. Therefore, using a polycarbonate printing technique, we developed a CO₂ incubator with a sealed heater that has a carbon/silica/aluminum oxide/titanium oxide ceramic coating and emits FIR upon heating [11]. This CO₂ incubator can stably emit FIR at wavelengths between 4 and 20 μm (maximum at 7 to 12 μm) under conditions of 100% humidity, 37.0 ± 0.5°C and 5% CO₂.

In this study, we used the FIR incubator to examine the effect of FIR on cell proliferation, morphology, cell cycle progression and apoptosis in A431, A549, HSC3, MCF7 and Sa3 human cancer cell lines. Furthermore, we performed comprehensive gene expression profiling of the cells using a cDNA microarray, and we examined the effect of overexpressing and suppressing candidate FIR response gene ATF3. Our results indicate for the first time that growth arrest following FIR irradiation in specific cancer cell lines is due to the expression of ATF3.

2. Materials and Methods

2.1 FIR Incubator

As previously reported [11], we fabricated an FIR radiant-panel incubator by coating a carbon/silica/aluminum oxide/titanium oxide ceramic (radiation efficiency > 97%) using a polycarbonate printing technique (Bloodissue Co. Ltd. Tokushima, Japan). The incubator can stably irradiate organisms with FIR at wavelengths between 4 and 20 μm (maximum at 7 to 12 μm) under conditions of 100% humidity, 37.0 ± 0.5°C and 5% CO₂ in air.

2.2 Calculation of Fir Absorbed Per 100-Mm Tissue Culture Dish in the FIR Incubator

FTIR (Fourier Transform Infrared Spectroscopy) analysis revealed that the ceramics coating inside the CO₂ incubator emits FIR at 4 W m⁻² str⁻¹ μm⁻¹ at wavelengths between 4.486 and 20.256 μm, with a maximal emission of 11.6 W m⁻² str⁻¹ μm⁻¹ at 9 μm, which is >95% of the emission rate of an ideal black body. Because the ceramic coating was maintained at 40°C, the total generating energy, integrated over the entire range of wavelengths, was calculated to be 130.225 W m⁻² str⁻¹. The total area of the FIR-emitting ceramic surface was 1.2385 m². Therefore, the total energy emitted into the incubator was 161.28366 W str. Assuming that FIR is emitted in all directions, the total emission was 2026.7502 J/sec. Given that the volume of the CO₂ incubator was 0.1257 m³ and the volume of culture medium was 6 ml, the amount of energy absorbed by each 100-mm culture dish was 0.09674 J/sec. The surface area of each 100-mm culture dish was 78.5 cm², so that the energy reaching the base of the dish was 0.0012323 J/cm². Thus, over a 1-h period 4.4352 J/h · cm² was absorbed by each 100-mm culture dish. Therefore, total energy of irradiated FIR was in proportion to irradiating time.

2.3 Cell Lines and Cell Culture

A549 human lung carcinoma cells, HSC3 human tongue squamous carcinoma cells and MCF7 human breast carcinoma cells were purchased from Health Science Research Resources Bank (Sennan, Japan). A431 human epithelial vulva carcinoma cells and Sa3 human gingival squamous carcinoma cells were purchased from RIKEN Cell Bank (Tsukuba, Japan). A431, A549 and MCF7 cells were cultured in Dulbecco’s modified Eagle’s medium/Ham’s F-12 nutrient mixture (Sigma, St. Louis, MO, USA). HSC3 and Sa3 cells were cultured in Eagle’s basal medium (Sigma). All culture medium was supplemented with 10% heat-inactivated fetal bovine serum, 100 μg/ml penicillin G, 100 μg/ml streptomycin sulfate and 250 ng/ml amphotericin B (Invitrogen, Carlsbad, CA, USA). Cells were maintained at 37°C in a humidified atmosphere of 5% CO₂ in air. The medium were replaced every 2 days.

2.4 Measurement of Cell Number and Growth

Cells (5 × 10⁴) were plated in triplicate in 24-well plates (Nunc, Roskilde, Denmark). The attached cell populations were measured on days 0, 2, 4, 6, 8 and 10 using 0.2% Trypan blue and a hemocytometer. Incorporation of 5-bromo-2’-deoxyuridine (BrdU) was used to determine the amount of DNA synthesis. DNA synthesis by proliferating cells was assessed using a BrdU labeling and detection kit III (Roche, Mannheim, Germany) according to the manufacturer’s protocol. Briefly, cells (5 × 10⁴ per well) were seeded in 96-well tissue culture plates (Nunc) and then placed in the FIR incubator for 4 days, and BrdU incorporation was measured during the logarithmic growth phase (i.e., before the cells were confluent) by treating the cells for 4 h at 37°C with 10 μM BrdU. BrdU incorporation was quantified by measuring the absorbance of the substrate reaction (405 nm) and the absorbance at the reference wavelength (590 nm) using an ImmunoMini NJ-2300 (System Instruments, Tokyo, Japan). Absorbance values directly correlated with the amount of DNA synthesis and therefore the number of proliferating cells.

2.5 Histochemistry

Cells were grown on 22-mm² glass coverslips in 6-well culture dishes (Nunc). After 4 days of FIR irradiation, the cells were observed with a CK40 phase contrast microscope (Olympus, Tokyo, Japan), fixed and stained with hematoxylin and eosin. For immunofluorescent staining of heat shock protein (HSP) 70, cells were washed in PBS (Phosphate Buffered Saline), fixed for 20 min in 4% paraformaldehyde in PBS, washed three times for 5 min each in PBS and blocked for 1 h at room temperature with
5% goat serum. Cells were incubated at 4°C overnight in 1:200 mouse monoclonal antibody to HSP70 (Stressgen, Victoria, Canada) in PBS containing 1 mg/ml bovine serum albumin. After washing, the cells were incubated with 1:400 FITC (Fluorescein isothiocyanate) - labeled goat anti mouse IgG (Santa Cruz Biotechnology, Santa Cruz, CA, USA). The localization of intracellular HSP70 protein was identified using a BX51 confocal microscope (Olympus) and a CoolSNAP CF digital camera (Roper Scientific, Trenton, NJ, USA) and calibrated using RS Image Express software (Roper Scientific).

2.6 Cell Cycle Analysis

Most cells were arrested at late G1 phase using the double-thymidine block method. Briefly, cells (1 × 10^6 per dish) were seeded in a 60-mm dish and cultured for 24 h in the appropriate growth medium, followed by 24 h in medium containing 2.5 mM thymidine (Wako, Osaka, Japan) for A431 and Sa3 cells or 3.0 mM thymidine for HSC3 cells. Cells were washed twice with PBS and incubated with standard medium for 24 h before second 24-h incubation with the same concentration of thymidine. Cells were incubated for 0, 24, 48, 72 or 96 h after the second treatment with thymidine. After removal with 0.25% trypsin-EDTA solution and washing with PBS (-) (Dulbecco’s phosphate buffered Saline without calcium chloride), the cells were fixed for 24 h in 70% (v/v) ethanol at −20°C. Finally, the cells were treated for 30 min with a mixture of RNase A and propidium iodide (PI), and the DNA content in 1 × 10^4 cells was determined from the PI fluorescence as measured using an EPICS XL-MCL System II flow cytometer (Beckman Coulter, Miami, FL, USA).

2.7 Measurement of Apoptosis (TUNEL Staining)

Apoptotic cells were identified using an Apo-BrdU in Situ DNA Fragmentation Assay Kit (Bio Vision, Mountain View, CA, USA). As recommended by the manufacturer, cells were seeded on circular sheets (Nishshin EM, Tokyo, Japan) in 35-mm tissue culture dishes (Nunc) and were incubated for 4 or 7 days. Cells were fixed in PBS containing 4% formalin for 30 min. After rinsing twice with PBS, cells were incubated with 50 μL of DNA labeling solution for 1 h at 37°C. After rinsing twice with PBS, 100 μL of antibody solution containing FITC-conjugated anti-BrdU antibody and rinse buffer was added and cells were incubated for 30 min at room temperature. Cells were stained with 100 μL PI/RNase Staining Buffer. As a positive control, cells were irradiated with 10J of 260 nm ultraviolet light (UV) using TFX-20 (Vilber Lourmat, Marne la Vallee, France) and then incubated for 24 h. Apoptotic cells were identified by fluorescence microscopy and the number of apoptotic cells in 10 randomly selected fields was measured and used to determine the apoptotic index.

2.8 Microarray Studies and Data Analysis

Four days after FIR irradiation, two control and two FIR-irradiated samples were prepared for microarray hybridization. Total RNA was extracted using a Qiagen RNeasy Mini Kit (Qiagen, Valencia, CA, USA) according to the manufacturer’s protocol. Agilent human 1A ver.2 microarray slides (Agilent Technologies, Palo Alto, CA, USA) were used for the hybridization. The quality of RNA samples was monitored using an Agilent 2100 bioanalyzer (200 ng each). To produce labeled cRNA (complementary RNA), high-quality RNA was amplified and labeled with Cy5- and Cy3-CTP (Amersham Biosciences, Buckinghamshire, UK) using a Low RNA Input Fluorescent Linear Amplification Kit (Agilent) according to the manufacturer’s protocol. After the amplification and labeling, the dye incorporation ratio was determined using a Nanodrop spectrophotometer and the ratios were within 10 to 20 pmol per μg cRNA, which is the range suggested by the manufacturer for hybridization. For hybridization, an Agilent 60-mer oligo microarray (Rev.7, SSC Wash/6-screw hybridization chamber) was used according to the manufacturer’s protocol. Briefly, 750 ng Cy3-labeled control and 750 ng Cy5-labeled MPP+-treated sample were mixed and incubated for 17 h with an SSC-washed microarray slide from an Agilent in Situ Hybridization Kit. Sample pairs were dye-swapped and processed at the same time. The washed slides were immediately dried under a stream of ultrapure N2 in an ozone-free atmosphere. After drying, the slides were scanned using an Agilent Technologies Microarray Scanner with the PMT setting at 770 for Cy5 and 670 for Cy3, the raw data were normalized and analyzed using GeneSpring 7.0 software (Silicon Genetics, Santa Clara, CA, USA). For normalization, per spot and per chip intensity-dependent (LOWESS) normalization was used to correct for the intensity-dependent ratio bias [12]. In addition, the following filters were applied to improve the quality of the data: eliminate saturated signal, eliminate non uniformity of background, eliminate non uniformity of feature, Feature Population Outlier, eliminate low signal feature of background signal + 2.6 × SD and eliminate P value < 0.01. Genes were further classified for process and function according to their GO term information (http://www.godatabase.org).

2.9 Stable Transfection of ATF3

The cDNA for full-length human ATF3 was a generous gift from Dr. T. Hai (Department of Medical Biochemistry, Ohio State University, Columbus, OH, USA). ATF3 cDNA was subcloned into the Xba I and Bam HI sites of pcDNA3.1 (-) (Invitrogen). Cells grown on 60-mm dish-
es were transfected with 8 μg of pcDNA3.1-ATF3 or pcDNA3.1 (Invitrogen) using Lipofectamine 2000 (Invitrogen) according to the manufacturer’s instructions. The transfected cells were selected with 400 μg/ml G418 (Sigma) and clones formed were collected and maintained separately in medium supplemented with 400 μg/ml G418.

2.10 Quantitative Real-Time RT-PCR Data Analysis
To determine the level of ATF3 mRNA quantitative real-time RT-PCR was carried out using a LightCycler and the Fast Start DNA Master SYBR Green I Kit (Roche). The reaction contained 50 ng of cDNA and 100 pmol of each primer in a final volume of 10 μl. The gene-specific primers were as follows: ATF3, 5'-AAA CTAGGCAATGTACTCTTCCG-3' (sense) and 5'-AT TTCAGGATACTGCACTGGTG-3' (antisense), and α-actin, 5'-ATAGCACAGCCTGGATAGCAACGTAC-3' (sense) and 5'-ATGTACTCTTCCG-3' (antisense). The concentration of Mg2+ was 3 mM. In all cases, a first phase of denaturation was performed at 95°C for 10 min. Amplification was carried out for cycles of denaturation at 95°C for 10 s, hybridization for 10 s (60°C for ATF3 and α-actin) and elongation at 72°C (10 s for ATF3 and α-actin). Product specificity was evaluated by melting curve analysis. Fluorescence data were analyzed using LightCycler Software Ver.3.5 (Roche). Crossing points were established using the second derivative method. The relative amount of target transcript in the sample was calculated by dividing the amount of target by the amount internal standard (α-actin). Results were expressed as the target/internal standard concentration ratio calculated from the calibration curve.

2.11 Protein Extraction and Western Blotting
Cells (1 × 106) were grown in 60-mm tissue culture dishes (Nunc). After removing the cell culture medium from the culture dishes (Nunc) and washing the cells twice with cold PBS (-), the cells were lysed in lysis buffer (20 mM Tris-HCl, pH 7.5, 150 mM NaCl, 1 mM Na2EDTA, 1% Triton X-100, 2.5 mM sodium pyrophosphate, 1 mM β-glycerophosphate, 1 mM Na3VO4, and 1 μg/mL leupeptin). Protein levels were measured by the Lowry method [13] using a DC Protein Assay Kit (Bio-Rad, Hercules, CA, USA). Cell lysate containing 20 μg of protein for ATF3 was subjected to SDS (Sodium Dodeyl Sulfate)-polyacrylamide gel electrophoresis. Separated proteins were then transferred from the gel to a polyvinylidene difluoride membrane. After blocking with 5% skim milk in PBS-Tween, the membrane was incubated for 1 h at room temperature with primary antibody in PBS-T containing 5% skim milk, followed by three 10-min washes with PBS-T. Next, the membranes were incubated for 1 h at room temperature with horseradish peroxidase-labeled secondary antibody and washed three times for 10 min with PBS-T. Immunoreactive protein was detected using an ECL plus kit (Amersham Biosciences) and visualization by exposure to Hyperfilm (Amersham Biosciences). The primary antibodies were used rabbit anti-human ATF3 (c-19; Santa Cruz Biotechnology), anti α-actin (Sigma) and the secondary antibody was horseradish peroxidase-conjugated anti-mouse (Zymed Laboratories, South San Francisco, CA, USA) or anti-rabbit IgG (Amersham Biosciences).

2.12 Knockdown of ATF3 by Antisense Oligonucleotides
The sequences of the sense and antisense ATF3 phosphorothioate oligonucleotides were previously described [14]. The scrambled oligonucleotide for ATF3 was 5'-ACGCAGGTGTACTCGGACCAGAGTAGTTGT-3'. On days 0 and 2, cells were transfected with oligonucleotides using Lipofectamine 2000 according to the manufacturer’s protocol. Four days after transfection, ATF3 mRNA was measured by real-time RT-PCR and cell proliferation was measured by BrdU incorporation.

2.13 Statistical Analysis
Data are means ± SE of quadruplicate samples at least in single experiments and duplicate experiments as described in the figure legends. Student’s t-test was used for comparisons between two groups. Multiple group comparisons were performed by one-way ANOVA followed by the Tukey-Kramer multiple group comparisons test. All statistical analyses were performed using Statcel 2 software (OMS publishing, Saitama, Japan).

3. Results
3.1 FIR Irradiation Selectively Inhibits the Growth of Specific Cancer Cell Lines
Although the proliferation of A549, HSC3 and Sa3 cells was significantly suppressed from day 6 of culture (59.0%, 75.4% and 76.2% respectively) up to at least day 10, FIR irradiation had little effect on the growth of A431 or MCF7 cells (Figure 1(a)). Measurement of BrdU incorporation on day 4 of culture also showed a significant suppression of growth by FIR irradiation in A549, HSC3 and Sa3 cells but not in A431 or MCF7 cells (Figure 1(b)). Observation of the morphology by phase contrast microscopy revealed that the cytoplasm and nucleus was enlarged in A549 cells. Some of the
HSC3 cells also showed hypertrophy of the cytoplasm and nucleus and others tended to show atrophy. Finally, some of the Sa3 cells showed hypertrophy of the cytoplasm (Figure 1(c)).

Figure 1. (a) Effect of FIR irradiation on cell growth of five cancer cell lines. Cells (1 × 10^5) were plated in 24-well dishes and cultured for 10 days. Cell numbers were counted every other day. Although proliferation of A549, HSC3 and Sa3 cells was suppressed from day 6 to 10 of culture, FIR irradiation had little effect on the proliferation of A431 and MCF7 cells. *P < 0.05 vs. control (unirradiated) cells; (b) BrdU incorporation assay on day 4 of culture. Cells (1 × 10^4) cells were plated in 96-well dishes and cultured for 4 days, and BrdU incorporation was measured. FIR significantly suppressed the proliferation of A549, HSC3 and Sa3 cells. *P < 0.05, **P < 0.01 vs. control (unirradiated) cells; (c) Hematoxylin and eosin staining of cells on day 4 of culture. In A431 cells, there were no noticeable differences between irradiated and control (unirradiated) cells. In A549 and MCF7 cells, the volume of the cytoplasm and nucleus was increased in the FIR-treated cells. In HSC3 cells, some FIR-treated cells showed hypertrophy of the cytoplasm and nucleus (arrows), and others tended to show atrophy. Finally, hypertrophy was observed in some Sa3 cells (arrow heads). bar:0.5 mm
3.2 Limited FIR Induces G2/M Arrest in HSC3 and Sa3 Cells

To determine whether FIR treatment of cancer cells alters cell cycle progression, we examined the A431, HSC3 and Sa3 cells by flow cytometry. In control cultures of HSC3 and Sa3 cells at 96 h, 54.7% and 74.9% of the cells were in G1 phase and 33.3% and 16.8% were in G2/M phase, respectively. In HSC3 and Sa3 cells treated with FIR, the fraction of cells in G1 decreased to 43.2% and 66.0% and the fraction in G2/M phase increased to 40.1% and 21.1%, respectively (Figure 2(a)). In A431 cells, the proportions in the different phases of the cell cycle were unaffected by FIR. The G2/G1 ratio in FIR-treated HSC3 was clearly higher than in the untreated (control) group and that in Sa3 cells was slightly higher in the FIR-treated cells than in the control cells (Figure 2(b)). Finally, in A431 cells, the G2/G1 ratio was not affected by FIR. These results suggest that FIR inhibits cell growth by inducing cell cycle arrest.

3.3 FIR Irradiation does not Induce Apoptosis

To determine whether the inhibition of proliferation by limited FIR was associated with apoptosis or necrosis, A431 HSC3 Sa3

A

<table>
<thead>
<tr>
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<th>A431</th>
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<th>Sa3</th>
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<td>S</td>
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Figure 2. (a) Flow cytometric analysis of the cell cycle in control (untreated) and FIR-irradiated cells. After double-thymidine block, cells were treated with FIR for 96 h, harvested, and DNA content was estimated by staining with PI; (b) Ratio of the G1 population vs. the G2/M population at 96 h

3.4 Genetic Analysis Reveals that ATF3 is a Potent Mediator of the Effects of FIR

We next examined the changes in gene expression induced by a 4-day irradiation with FIR using an Agilent Human cDNA microarray, in order to find a first reacted gene and the functional genes in early stage. Of the 19,000 genes examined, FIR caused a more than 1.5-fold change (P < 0.01) in the expression of 32, 166, 98, 33 and 34 genes in A431, A549, HSC3, MCF7 and Sa3 cells, respectively (Table 1). We made analysis on the 10 most up-regulated and 10 most down-regulated genes by FIR of these cell lines (data not shown). In addition, we searched for genes that were differentially expressed between the “FIR sensitive” group (A549, HSC3 and Sa3 cells) and the “less sensitive” group (A431 and MCF7 cells) (Figure 4). This analysis identified ATF3, BBC3 and PNRC1 as candidate mediators of the FIR effect. The expression of ATF3 was up-regulated by FIR in the FIR-sensitive group but unchanged by FIR irradiation in the less sensitive group. The expression of BBC3 and PNRC1 was unchanged by FIR in the FIR-sensitive group but was down-regulated in the less sensitive group. Of these three genes, we focused on ATF3 because it was reported to be up-regulated in response to various stresses [15] and to play a crucial role in the suppression of proliferation in HeLa cells [16].

3.5 Overexpression of ATF3 Suppresses Cell Proliferation in A431, HSC3 and Sa3 Cells

To verify the role of ATF3 in the effects of FIR, we developed A431, HSC3 and Sa3 cell lines stably expressing human ATF3 (A431-ATF3, HSC3-ATF3 and Sa3-ATF3 cells, respectively). Control cells were wild-type (A431 WT, HSC3 WT and Sa3 WT) and empty vector-transfected (A431 Neo, HSC3 Neo and Sa3 Neo) cells. To determine whether increased expression of ATF3 mRNA and protein were analyzed by Real-time RT-PCR and Western blot analysis (Figures 5(a) and (b)). The expressions of ATF3 mRNA were activated 1.7, 12.0 and 3.3 times in A431-ATF3, HSC3-ATF3 and Sa3-ATF3 cells, respectively comparing with Neo (Figure 5(a)). It was testified that protein expression was clearly activated (Figure 5(b)). Then, the cell proliferation of A431-ATF3
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4. An Antisense Oligonucleotide Targeting ATF3 Prevents Fir Suppression of Cell Growth

To confirm whether inhibition of ATF3 expression affected cell growth or not, we examined the effect of knocking down ATF3 using an antisense oligonucleotide on cell proliferation by BrdU assay. HSC3 cells were selected for this experiment, because they expressed the highest level of ATF3 following FIR irradiation in the five cell lines tested A431, HSC3, Sa3, A549 and MCF7 cells. The inhibition of ATF3 mRNA expression was made sure by real-time RT-PCR (Figure 6(a)). Antisense oligonucleotide AS1 (30 nucleotide from 5’ terminal of ATF3 mRNA) was inhibited 65.9% compared with LF (only Lipofectamine 2000) (Figure 6(a)). Then, Antisense oligonucleotide AS2 (30 nucleotides from 120 nucleotide to 150 nucleotide from 5’ terminal of ATF3 mRNA) was inhibited 65.9% compared with LF (only Lipofectamine 2000) (Figure 6(a)). The effect of ATF3

Table 1. Number of genes significantly regulated by FIR on day 4 of irradiation. Fold change indicates the relative expression in FIR irradiated vs. un-irradiated control cells. Genes were judged to be Up-regulated or Down-regulated based on log ratio that were 1.5 fold or greater

<table>
<thead>
<tr>
<th>Gene</th>
<th>A431</th>
<th>A549</th>
<th>HSC3</th>
<th>MCF7</th>
<th>Sa3</th>
<th>Total by FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up-regulated</td>
<td>4</td>
<td>55</td>
<td>68</td>
<td>10</td>
<td>13</td>
<td>150</td>
</tr>
<tr>
<td>Down-regulated</td>
<td>28</td>
<td>111</td>
<td>30</td>
<td>23</td>
<td>21</td>
<td>213</td>
</tr>
<tr>
<td>Total by cell</td>
<td>32</td>
<td>166</td>
<td>98</td>
<td>33</td>
<td>34</td>
<td>363</td>
</tr>
</tbody>
</table>

Figure 4. The five cell lines were divided into FIR-sensitive (A549, HSC3 and Sa3) and less sensitive groups (A431 and MCF7) according to the suppression of cell growth by FIR (using 80% of control as a threshold) on day 6 of culture. The genes differentially expressed in FIR-sensitive and the less sensitive groups were extracted. Genes were judged to be up-regulated or down-regulated when log ratios were 1.5 fold or greater.
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knockdown on proliferation was made sure by WST-1 assay. The effect of knocking down ATF3 using an antisense oligonucleotide on the cell proliferation of HSC3 cells was made sure by BrdU assay (Figure 6(b)). The proliferation of Anti-sense oligonucleotide AS1 cells was inhibited 47.1% by FIR, in the other side, it of LF cells was inhibited 59.4% by FIR (Figure 6(b)). Therefore, the effect of knocking down ATF3 suppressed 20.1% of the effect to inhibit the proliferation by FIR. Similarly, the proliferation of Anti-sense oligonucleotide AS2 cell was inhibited 45.9% by FIR, the effect of knocking down ATF3 suppressed 22.7% of the effect to inhibit the proliferation by FIR. Similar data were obtained in the other two types of cells (data not shown).

5. Discussion

In this study, we showed that FIR radiation suppresses the proliferation of A549, HSC3 and Sa3 cells. In HSC3 and Sa3 cells, this was due to G2 arrest. Two other cell lines, A431 and MCF7, showed almost no growth arrest in response to FIR radiation. A549 is from lung gland, HSC3 is from a tongue epithelium and Sa3 is from upper gingival squamous cell. A431 is from vulva epithelium and MCF7 is from mammary gland. The special characteristics on the cell source could not be found in these results.

We investigated the effect of FIR on gene expression using a DNA microarray and found that FIR radiation tended to induce RNA processing in FIR-sensitive cells, especially A549 and HSC3 cells, and to induce more down-regulated genes than up-regulated genes in all cells except for HSC3 cells (Table 1). These genes affected by FIR seemed to be contained many transcription factors and transcription regulating factors. Generally, it was suggested that the effects of FIR radiation do not promote gene transcription, but suppressed it. Thus, we thought the clue of lower proliferation of the FIR-sensitive cancer cells was the inhibition of cell cycle dependent genes, cause of apoptosis are not induced by FIR.

Formerly, we examined on the expression of the genes competing to the stress to find that the basal expression level of heat shock protein (HSP) 70A controlled the effect of FIR radiation [17]. In addition, it was reported that HSP70 is an antiapoptotic chaperone protein that inhibits mitochondrial release of cytochrome c and blocks procaspase-9 recruitment to the apoptosome complex [18,19]. According to our previously study, apoptosis in the FIR-insensitive MCF-7 and A431 cells relating to their high expression of HSP70A could not be induced. Furthermore, FIR didn’t induce apoptosis even in the FIR sensitive HSC3, Sa3 and A549 cells whether HSP70A expression in these cells is relatively lower. In current study, FIR was found to cause hypertrophy without apoptosis in all three sensitive cell lines, al-

Figure 5. (a) Real-time RT-PCR analysis of ATF3 mRNA in wild-type (A431 WT, HSC3 WT and Sa3 WT), empty vector-transfected (A431 Neo, HSC3 Neo and Sa3 Neo), and ATF3-transfected (A431-ATF3, HSC3-ATF3 and Sa3-ATF3) cells. Values shown in vertical axis are the fold expression relative to wild-type cells and adjusted for actin. *P < 0.05 vs. empty vector-transfected cells; (b) Western blot analysis of ATF3 in wild-type, empty vector-transfected and ATF3-transfected cells; (c) Compared to empty vector-transfected cells, overexpression of ATF3 suppressed cell proliferation from day 6 in A431 cells and from day 4 in HSC3 and Sa3 cells, *P < 0.05 vs. empty vector-transfected cells; (d) Phase contrast image of ATF3-transfected cells. Overexpressing cells of ATF3 induced hypertrophy (arrows) in HSC3 and Sa3 cells.

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we calculated there must be another anti-apoptotic mechanism and clue explanation except of HSP70A. Overall, FIR seemed to delay the cell cycle, cause changing in the cytoskeleton, and induce some necrosis without inducing apoptosis. It was suggested that FIR radiation did not directly induce apoptosis of cancer cells in vitro and this indication may be related of natural character of FIR.

Still more, we identified ATF3 as a gene whose expression correlated closely with the growth arrest by FIR. For this reason, the expression of ATF3 was up-regulated by FIR in the FIR-sensitive group but unchanged by FIR radiation in the less sensitive group providing by microarray analysis, thus we speculated ATF3 can be a mediator of FIR. Therefore, the expressions of ATF3 mRNA were activated 1.7, 12.0 and 3.3 fold times in A431-ATF3, HSC3-ATF3 and Sa3-ATF3 cells, respectively and the cell growth arrest effect of FIR is more activated comparing with the Neo-groups. In another hand, this repressor effect of FIR is significantly inhibited by using antisense oligonucleotide of ATF3. These results were supported by the current study, Udagawa et al., reported that the whole body hyperthermia with FIR inhibited the growth of spontaneous mammary tumors in mice [1], Teraoka et al., found that FIR at wavelengths between 4 to 16μm inhibits the growth of HeLa cells in vitro at 37°C [10] and by Fan et al., the overexpression of ATF3 has been previously shown to retard G1 to S phase progression in HeLa cells [16].

ATF3 is a member of the ATF/CREB family of transcription factors [20]. ATF3 mRNA and protein levels are relatively lower in most normal and quiescent cells [15,21,22]. ATF3 appears to participate in the JNK/SAPK and IFN-PKR pathway [23,24] and activated by many variant of stimulation including cytokines, genotoxic agents, growth factors such as fibroblast growth factor, epidermal growth factor and hepatocyte growth factor, pro-apoptotic stimuli such as lipopolysaccharide, oxidative stress and compounds with antitumorigenic activities such as the phosphatidylinositol 3-kinase inhibitor LY294002, nonsteroidal antiinflammatory drugs, progesterone and dietary polyphenols as a curcumin from the tumeric plant and catechins in green tea [16,20,21, 25,26,27-33]. ATF3 also might be involved in homeostasis, wound healing, regenerating liver, cell adhesion, cancer cell invasion and apoptosis [21,22,34-38].

In our study, the expression of ATF3 has been keeping in the high level even in 4 days after the FIR treatment and staying at the one same level stably and continuously. Most results of the others on the expression level of ATF3 had showed immediate and transient [15,21,22,38]. For example, Fan et al., that treatment of RKO cells with 20 Gy of IR or 10 J•m⁻² of UV light results in a rapid induction of ATF3 expression that peaks after 8 h and returns to the basal level within 24 or 36 h for IR and UV light, respectively [16], the induction of ATF3 mRNA
and protein was peaked at 1 h and 2 h after Doxorubicin treatment in cardiac myocytes [39], ATF3 mRNA is rapidly increased in 30 min after TNF-α stimulation in HUVECs and ATF3 protein was also induced with maximum accumulation in 4 h and involved TNF-α induced HUVECs apoptosis in atherosclerotic region [26,39]. Kawauchi et al., reported that the level of ATF3 increased within 4 h after TNF-α stimulation in HUVECs and protected HUVECs from TNF-α inducible cell death by down-regulating the activity of pro-apoptotic gene p53 [40], ATF3 is induced in ovarian cancer cell lines by progesterone after 4 h of culture [31], the increase in ATF3 mRNA was evident in the earliest time point 4h and was maintained through 24 hours of curcumin treatment in some human cancer cell lines [32]. The difference of ATF3 induction period in our study might be related of natural character of FIR. Because FIR is not brother such some rays UV, IR and similarly to physiologic response without cytotoxic reaction, and FIR has sub-lethal character, its energy is similar to intracellular molecular energy. Connectively with this notion, some stress stimuli such as anisomycin at a subinhibitory concentration can induce ATF3. Therefore anisomycin treatment stabilized ATF3 mRNA affecting to several AUUA sequences, which have been demonstrated to destabilize mRNA [38,41-43]. Thus we speculated FIR also may affect to these sequences by similar mechanism as a anisomycin. It is provided any other precisely works. Surely, stably and continuously induction of ATF3 by FIR is caused of stimuli dependent. Our colleagues and others considered that the continuous expression of FIR may have a different function on the cells [36].

ATF3 acts as a transcriptional repressor as a homodimer, although the same protein functions as a transcriptional activator in heterodimeric form [38,43]. Then we propound the hypothesis, that ATF3 as a transcriptional repressor under the continuous expression can inhibit the activity of pro-apoptotic genes such as p53, etc [40] although many studies have shown ATF3 is pro-apoptotic gene [32,36]. In contrast, some works demonstrated that ATF3 is anti-apoptotic gene [26,39,40]. Recently, researchers concurred that ATF3 can play both pro-apoptotic and cell survival role depending on the type of stimulation and cell context [21,26,32,36,39]. In our study, there were shown the cell hypertrophy of FIR-sensitive cell lines without apoptosis. It may be related of stimuli context-FIR and can be explained ATF3 reacted little adaptive response by inducing of FIR in the cancer cells. Therefore, Okamoto et al., reported that ATF3 specifically in the heart under the control of the α-myosin heavy chain promoter have atrial enlargement, and atrial and ventricular hypertrophy similarly to our results providing that ATF3 can be a mediator of FIR. Actually, the cellular biology consists of complex mechanism. Thus only FIR may not induce apoptosis, because its character is sub-lethal. Farther, we should study the effect of FIR in vivo, because there will be the possible that FIR can induce cancer cell apoptosis in vivo. Really FIR will not induce cancer cell death, the cell growth arrest effect of FIR that is reported in currently study remarkably caused of suppression of cell growth.

Liang et al., noticed two main classes of binding sites are placed in the promoter of ATF3 gene. One is the inducible site such as the ATF/CRE, AP1 and NF-kB sites; the other is the site implicated in cell cycle regulation, such as Myc/Max and E2F binding sites [20]. Certainly, ATF3 may play role on the cell cycle, because there are several relating sites on its promoter. This notion is supported by others study, that ATF3 has been shown to involve cell proliferation, invasion and other function by regulating own target genes such as Thrombospondin, Decorin, E-selectin, gluconeogenic enzymes, Gadd153/Chop10 and Osteocalcin via CREB/activator protein-1 (AP-1) motifs [34,37,44,45]. Thus we speculated FIR induced ATF3 as a its mediator on the sensitive groups of human cancer lines, farther ATF3 influenced to the proliferation of cancer cells by regulating its own target genes, which is attended on the cell cycle arrest the G2/M phase in vitro. Our this intention is supported by these studies: First on the effect of FIR, Udagawa et al., reported that the whole body hyperthermia with FIR inhibited the growth of spontaneous mammary tumors in mice [1-3], Teraoka et al., found that FIR at wavelengths between 4 to 16μm inhibits the growth of HeLa cells in vitro at 37°C [10]. Second on the antitumorigenic function of ATF3, by Fan et al., have shown that the overexpression of ATF3 prolonged G1/S phase in HeLa cells, consistently to this study by Lu et al., the ATF3 can function the cell growth arrest in the G1/S phase by inhibiting cyclin D1, by Kang et al., ATF3 and Smad3 complex can inhibit the growth of cancer cells by repressing Id1. Third, ATF3 is induced by antitumourigenic agents including nonsteroidal antiinflammatory drugs, the phosphatidylinositol 3-kinase inhibitor LY-294002, progesterone and dietary polyphenols as a curcumin from the tumeric plant and catechins in green tea [21,25,29-33].

On the theme of these works, we represented the possible molecular mechanism in our study (Figure 7). Our previously study also showed that the limited FIR inhibited growth, invasion and metastasis of human vulva A431epithelial cancer cells by significantly inhibiting the expression of matrix metalloproteinase (MMP) members MMP-1, MMP-9, MMP-10 and MMP-13 [9]. In the consistent, the MMP-2 gene expression which participates in cancer cell invasion is down-regulated by ATF3 via the suppression of p53 trans-activation on the MMP-2 promoterregion [46]. Stearns et al., have re-
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Recent literatures indicated that some of the signals can induce ATF3 gene expression do not fit the conventional definition of stress signals [47] and ATF3 as an adaptive-response gene that participates in cellular processes to adapt to extra- and/or intracellular changes [47, 48], although there are many studying works reported that ATF3 is a oncogene [22,49,50]. Actually, ATF3 enhances apoptosis in the untransformed MCF10A mammary epithelial cells (spontaneously immortalized mammary epithelial cell line), but protects the aggressive MCF10CA1a cells (high grade malignant cell line) and enhances its cell motility [51]. Similarly to this study, ATF3 is differentially expressed in the metastatic sublines of B16 melanoma but not in the parental B16 cells. Furthermore, introduction of ATF3 into the low metastatic B16 cells can convert it into high metastatic cells [52]. ATF3 was also reported recently to be highly expressed in classic Hodgkin’s lymphoma but not in the non-Hodgkin’s lymphoma, and blockade of ATF3 by siRNA reduced proliferation and viability of the Hodgkin’s lymphoma cells [53].

In conclusion, it was found that a body temperature range of FIR radiation inhibited proliferation of A549, H5C3 and Sa3 cells by G2/M arrest through enhancing the expression of ATF gene and induced cell hypertrophy without apoptosis. We also considered stably and continuously expression of ATF3 may play important roles in the effect of FIR by depending on stimuli context-FIR natural character. These findings can support that FIR may be a effective factor for treatment of cancer.

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1053-1060.


Voltage Generation by Rotating an Arbitrary-Shaped Metal Loop around Arbitrary Axis in the Presence of an Axial Current Distribution

Constantinos A. Valagiannopoulos

National Technical University of Athens, School of Electrical and Computer Engineering, Division of Electromagnetics, Electrooptics and Electronic Materials, Athens, Greece.
Email: valagiannopoulos@gmail.com

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ABSTRACT

A thin metallic wire loop of arbitrary curvature is rotated with respect to an arbitrary axis of its plane. The device is excited by an electric dipole of infinite length and constant current. The resistance of the loop is computed rigorously as function of the position of the source. In this way, the induced voltage along the wire, under any kind of axial excitation, is given in the form of a superposition integral. The measured response is represented for various shapes of the coil, with respect to the time, the rotation angle and the position of the source. These diagrams lead to several technically applicable conclusions which are presented, discussed and justified.

Keywords: Electromagnetic Induction, Arbitrary-Shape Loop, Axial Current Excitation, Superposition Integral

1. Introduction

Electromagnetic (EM) induction is the production of voltage across a conductor situated in a changing magnetic field or a conductor moving through a stationary magnetic field. The physics that govern the inductive experiments have been mathematically examined in a number of old and elementary studies. The relationship between the various induction laws is summarized in [1] where Cohn advocates that the combined use of both motional and transformer induction assures the validity of the produced results. The Faraday’s disk, the typical DC generator, a cumulative magnet and other inductive structures are thoroughly investigated. Hvozdara also has contributed significantly in analyzing and solving rigorously some basic configurations where the EM induction phenomenon appears. For example in [2], the magnetotelluric field for a cylindrical inhomogeneity in a half space with anisotropic surface is evaluated, while in [3] is shown theoretically what effects are generated if one considers the rotation of a spherical Earth in an external inhomogeneous time-variable magnetic field. Moreover, a rudimentary study of induction in a rotating conductor surrounded by a rigid conductor of finite or infinite extent has been provided in [4]. The analysis is based on integral solutions of the field equations and leads to the conclusion that the induced magnetic fields depend on the relative symmetry of the rotator.

Many solving techniques have been utilized to convert the aforementioned theoretical analyses into practical applications in real-world configurations. For example in [5], a 3-D finite-element general method is presented to treat controlled-source induction problems in heterogeneous media. It can be used efficiently for EM modeling in mining, groundwater, and environmental geophysics in addition to fundamental studies of EM induction within a heterogeneous environment. Furthermore, many patents and inventions such as [6], exploit inductive phenomena to generate high-voltage power. In particular, the power capability of core-type transformers is increased by creating additional magnetomotive force in certain secondary coils without any subsequent power loss. Also in [7], a highly applicable technique is presented which describes finite-difference approximations to the equations of 2-D EM induction that permits discrete boundaries to have arbitrary geometrical relationships to the nodes.

Apart from the old standard textbooks and the newer
technical reports, there are numerous recent, state-of-the-art references examining devices and presenting techniques which exploit electromagnetic induction. In [8], a new electromagnetic induction detection mode for Capillary Electrophoresis (CE) and microfluidic chip CE has been presented. Its own optimal operating conditions are determined, and its application in CE and microfluidic chip CE of inorganic ions is described. A study [9] tests the validity of using electromagnetic induction (EMI) survey data, a new prediction-based sampling strategy and ordinary linear regression modeling to predict spatially variable feedlot surface manure accumulation. In addition, a flow injection system incorporating electromagnetic induction heating oxidation for on-line determination of chemical oxygen demand has been proposed [10]. The procedure utilizes induction heating instead of conventional reflux heating, with acidic potassium dichromate acting both as an oxidant and as a spectrometric reagent. Finally, a general-purpose analysis is contained in [11], where the law of induced electromotive force is applied to three significant cases: moving bar, Faraday’s and Corbino’s disc.

In this work, we assume a closed metallic wire of arbitrary shape which is mechanically rotated with respect to an arbitrary axis of its plane, in the presence of an elemental source of infinite length and constant current. The parametric equation of the wire curve is extracted through coordinate transformations and the magnetic flux through the loop is evaluated straightforwardly. To this end, we apply the Faraday’s law and an expression for the coil’s resistance is derived. This study examines the voltage induction to the most general case of a single wire loop (shape and rotation axis can be altered at will) which has not been treated rigorously yet. However, the basic novelty of the present analysis is that, due to the linearity of the participating operators, the calculus can be generalized to cover any case of axial excitation. We compute a kind of “Green’s function” ([12]) for the loop impedance, corresponding to a point source excitation. Therefore, the solution for more complex axial currents utilized in industry and technology is given through an integral of that resistance function multiplied by the current distribution of the source. A set of computer programs has been developed to evaluate the formulas, the induced voltage is represented as function of the time, the rotation angle and the position of the source for various loop shapes, while the produced graphs are presented and discussed.

2. Problem Statement

The Cartesian coordinate system \((x, y, z)\) defined in Figure 1(a) will be used throughout the analysis. We suppose an infinite axial dipole into vacuum, parallel to \(y\) axis, at the position \((x = X, z = Z)\), flown by a constant current \((x = X, z = Z)\) (in Amperes). A wire loop is located around the origin \(O\) on the \((x, y)\) plane, and its shape is determined by the radial distance \(P(\varphi)\) (polar function) where \(\varphi\) is the (unprimed) azimuthal angle of our consideration. This closed curve of a perfectly conducting material and infinitesimal thickness is rotated periodically around the arbitrary axis \(\varphi = \pi / 2 - \xi\) with circular frequency \(\omega\), as shown in Figure 1(b). Consequently, it makes sense just to examine the loop turned by the representative angle \(\omega t\) with

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) The physical configuration of the device. An arbitrary-shaped loop is rotated periodically, in the presence of an infinite dipole, with respect to an axis parallel to the source; (b) The rotation is carried out with respect to an arbitrary axis
respect to the aforementioned axis. Initially \((t = 0)\), the curve lies entirely on the \((x, y)\) plane.

The purpose of this work is to obtain an expression for the electromotive force induced at the coil, being dependent on the time \(t\), the rotation axis \(\xi\) and the shape of the loop \(P(\varphi)\). The generated voltage should certainly vary with the position of the primary source \((X, Z)\), and thus the derived formula could be used in studying structures with more complicatedly distributed excitation current.

3. Mathematical Formulation

Firstly, we should extract the parametric equation set of the rotated loop when \(\xi = 0\) as appeared in Figure 1. The equations will be denoted by \(\{x = x(\varphi), y = y(\varphi), z = z(\varphi)\}\) and the azimuthal angle \(\varphi \in [0, 2\pi]\) will play the role of the parametric variable even when the object does not belong exclusively to \((x, y)\) plane. As the closed wire is rotated with respect to \(y\) axis, the corresponding coordinate \(y(\varphi)\) will be fixed, independent from the angle \(\omega t\) and equal to \(P(\varphi)\sin \varphi\). The rest two equations are derived by projecting the other edge of length \(P(\varphi)\cos \varphi\), which is posed at angle \(\omega t\), upon the axes \(x\) and \(Z\). Accordingly, one obtains the following expressions:

\[
x(\varphi) = P(\varphi)\cos \varphi \cos \omega t, \\
y(\varphi) = P(\varphi)\sin \varphi, \\
z(\varphi) = -P(\varphi)\cos \varphi \sin \omega t.
\]

In order to find the parametric equation of the curve when \(\xi \neq 0\), we use the primed coordinate system \((x', y', z')\) which is received through rotation of the unprimed one by angle \(\xi\) with respect to axis \(Z\) (defined in Figure 1(b)). The polar equation of the loop is now given by \(\Pi(\varphi') = P(\varphi' - \xi)\), while the two azimuthal angles are connected obviously via the relation \(\varphi' = \varphi + \xi\). Therefore, we take the Formulas (1)-(3) replacing \(\varphi\) by \(\Pi\) and the unprimed variables \(\{x, y, z, \varphi\}\) by the primed ones \(\{x', y', z', \varphi'\}\). In this sense, the parametric set of the primed coordinates with respect to unprimed azimuthal angle \(\varphi\) (after trivial algebraic manipulations), is written as follows:

\[
x'(\varphi) = P(\varphi)\cos (\varphi + \xi) \cos \omega t, \\
y'(\varphi) = P(\varphi)\sin (\varphi + \xi), \\
z'(\varphi) = -P(\varphi)\cos (\varphi + \xi) \sin \omega t.
\]

The parametric equations of the arbitrarily rotated wire loop expressed in the unprimed coordinate system are denoted by \(\{x = x(\varphi, t), y = y(\varphi, t), z = \zeta(\varphi, t)\}\) and are determined from the transformation relation below [13]:

\[
\begin{bmatrix}
    x'(\varphi) \\
y'(\varphi) \\
z'(\varphi)
\end{bmatrix}
= 
\begin{bmatrix}
    \cos \xi & \sin \xi & 0 \\
    -\sin \xi & \cos \xi & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x(\varphi, t) \\
y(\varphi, t) \\
z(\varphi, t)
\end{bmatrix}.
\]

An extra time argument has been added to the dependencies of the parametric equations for better comprehension.

Once the boundary of the rotating wire is rigorously specified, the field quantities related to the induced voltage can be computed. The magnetic vector potential of a \(y\)-polarized infinite dipole into vacuum at distance \(D\) from its axis is given by [14]:

\[
A(D) = y \frac{\mu_0}{4\pi} \ln \left( \frac{D}{D_0} \right),
\]

where \(D_0\) is the reference distance, \(\mu_0\) is the vacuum magnetic permeability and \(y\) is the unitary vector of the \(y\) axis. The transverse distance of the representative loop point with azimuthal angle \(\varphi\), at an arbitrary time \(t\), from the axis \((x = X, z = Z)\), is found apparently equal to:

\[
D(\varphi, t, X, Z) = \sqrt{(X - x(\varphi, t))^2 + (Z - \zeta(\varphi, t))^2},
\]

also shown in Figure 2. It is well-known [15] that the magnetic flux through a closed loop \((W)\) is defined from the line integral of the magnetic potential on the curve, that is \(\Phi = \int_W A \cdot dW\). In our case, this formula is particularized [16] to give:

\[
\Phi(t, X, Z) = \frac{\mu_0}{2\pi} \ln \left( \frac{D(\varphi, X, Z)}{D_0} \right) \psi_{\varphi}(\varphi, t) d\varphi,
\]

where the subscript notation is used for the partial derivative of a function. It should be noted that the magnetic flux is independent from the reference distance \(D_0\). According to Faraday’s law, the induced electromotive force is given by the time derivative of magnetic flux \(U = -d\Phi / dt\); therefore, it is sensible to define the following auxiliary resistance function by excluding \(I(X, Z)\) from (10):

\[
R(t, X, Z) = 
- \frac{\psi_{\varphi}(\varphi, t)}{\frac{D(t, X, Z)}{D_0}} \int_0^{2\pi} D(\varphi, t, X, Z) \ln \left( \frac{D(\varphi, X, Z)}{D_0} \right) \psi_{\varphi}(\varphi, t) d\varphi
\]

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Figure 2. The transversal distance between the axis of the dipole and a representative point of the rotated loop projected on x-z plane

In this way, the generated voltage on the coil due to the self-rotation, in the presence of a dipole posed along the axis \((x = X, z = Z)\), is given by:

\[
U(t) = I(X, Z)R(t, X, Z)
\]  
(12)

In case the structure is excited by an axial surface current distributed according to the law \(K(X, Z)\) (measured in \(A/M\)) , along the line \((L)\), the induced electromotive force on the wire loop, is expressed in terms of the following line integral:

\[
U(t) = \int_{(L)} K(X, Z)R(t, X, Z)dL
\]  
(13)

Such an expansion is permissible because the operator

\[-\frac{d}{dt}\left(\int_{(W)} \*dW\right)\]

applied on \(A\) to find \(U\), is linear.

Similarly, if the excitation is a volume axial current \(J(X, Z)\) (measured in \(A/m^2\)), across the area \((S)\), the voltage is obtained through the double integral below:

\[
U(t) = \int_{(S)} J(X, Z)R(t, X, Z)dS
\]  
(14)

4. Indicative Results

In this section, we examine the produced voltage by rotating loops of variable shape and the effect of their geometrical parameters on it. The described method is applied to two families (A, B) of wire boundaries possessing the following polar equations:

\[
P_a(\varphi, a, b, n) = a \cos^{2n} \varphi + b \sin^{2n} \varphi,
\]  
(15)

\[
P_b(\varphi, a, b, n) = \frac{ab}{\sqrt{a^2 \cos^{2n} \varphi + b^2 \sin^{2n} \varphi}}
\]  
(16)

The arguments \((a, b)\) have length dimension and the argument \(n\) is a positive integer number. For brevity, we chose to excite the structure exclusively through point sources avoiding surface or volume distributions described through (13), (14). The following graphs will exhibit the dependencies of the produced voltage \(U(t)\) and the corresponding RMS value:

\[
U_{RMS} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} U^2(t)dt}
\]  
(17)

A single wire loop is not practically used for voltage generation as clusters of coils are utilized instead. We are more concerned for the qualitative description of the output quantity than measuring the exact magnitude (in Volts) of the produced voltage which is extremely small. Accordingly, the so-called “normalized voltage” is represented alternatively which is evaluated by replacing the magnetic permeability of the vacuum \(\mu_0 = 4\pi \cdot 10^{-7}\) \(N/A^2\) in (11), by unity. Each figure below is divided into two subfigures, the first of which is a diagram depicting the variation of the investigated quantities for various shapes of the loop, while the second is a polar plot of the corresponding wire boundaries.

In Figure 3(a), we represent the time dependence of the developed normalized voltage for various shapes of loops corresponding to different \(n\) parameters of the curve family A with constant \(a = 1 \, m\) and \(b = 2 \, m\). The observation duration is a single period as from that point on the procedure and the results are repeated unchanged. Even though the shape of the wire is arbitrary, the waveforms exhibit typical sinusoidal behavior, a fact that can be attributed to the horizontal and vertical symmetry of the metallic loop boundary. Also, the amplitude of the oscillation gets greater, as the area of the closed wire increases. This is a natural conclusion because by keeping fixed the rotation frequency and the axis parallel to the dipole, larger loops lead to more significant magnetic flux variance and implicitly to more substantial output voltage. Therefore, the oscillation amplitude of the investigated quantity is decaying with increasing \(n\) because the occupying area of the loop is greater for \(n = 1\) than for \(n = 6\) as shown in Figure 3(b).

In Figure 4(a), the variation of the RMS value of the induced voltage is depicted as function of the rotation angle \(\xi\) for three loop boundaries corresponding to different lengths \(b\) of the curve family A with constant \(a = 2 \, m\) and \(n = 2\). For \(\xi = 0\), the measured response is locally minimized when \(b = 2.5 \, m\) and maximized...
when $b = 1.5 \, m$. That is because the larger lobes of the curve extend close to the rotation axis in the first case and far from it in the second one as appeared in Figure 4(b). When $a = b$, all the four lobes of the curve are of the same size, which means that the global maximum at $\xi = 90^\circ$ reflects the rule according to which, better induction results are achieved when the current axis crosses normally the rotation axis of the coil. When $b = 2.5 \, m$, substantial voltage is produced for a rotation angle close to $\xi = 45^\circ$, where the response is poor in the case of $b = 1.5 \, m$. Needless to say that the graphs are symmetrical with respect to $\xi = 90^\circ$, due to the canonical shape of the loops.

![Figure 3](image3.png)

**Figure 3.** (a) The normalized voltage as function of time for various shapes of the loops. (b) The corresponding polar plots of the bounds. Plot parameters: $\xi = 0^\circ$, $X = -5 \, m$, $Z = 0 \, m$, $\omega = 100 \pi \, rad/sec$, $D_0 = 1 \, m$, $I = 1 \, A$, $a = 1 \, m$, $b = 2 \, m$.

In Figure 5(a), we represent the produced voltage as function of the horizontal position of the source $X$ for three metallic loops with shapes taken from the curve family B for various parameters $n$ ($a = 1 \, m$ and $b = 2 \, m$). With increasing $X$, namely when the source gets closer to the loop, the induced voltage takes more substantial values. Such a conclusion is sensible because the effect of the field gets stronger and consequently, the change in magnetic flux through the closed loop (from a maximum point to zero) takes larger values. Mind that the increase is much more rapid for $n = 3$ than in the other cases, a result which is attributed to the negligible distance between some points of this loop and the singular excitation axis when $X \to -2m$. Along this region, the recorded magnitude is much higher compared to other measurements of similar configurations such as

![Figure 4](image4.png)

**Figure 4.** (a) The RMS voltage as function of the rotation angle for various shapes of the loops; (b) The corresponding polar plots of the bounds. Plot parameters: $X = -5 \, m$, $Z = 0 \, m$, $\omega = 100 \pi \, rad/sec$, $D_0 = 1 \, m$, $I = 1 \, A$, $a = 2 \, m$, $n = 2$. Copyright © 2010 SciRes.
Voltage Generation by Rotating an Arbitrary-Shaped Metal Loop around Arbitrary Axis in the Presence of an Axial Current Distribution

these of Figure 4(a). On the other hand, when the primary source gets farther from the rotated wire, its shape plays a rather insignificant role and the differences are mainly attributed to the size of the loop.

In Figure 6(a), the variation of the induced voltage is represented as function of the vertical position of the excitation $Z$ (the source is moving normally to the plane of the sheet) for various loops from curve family $B$ corresponding to different lengths $b$ (with fixed $a = 1.5 \, m$ and $n = 1$). In all the three cases the response is maximized for $Z = 0$ which is a natural result because the loop is at the closest distance from the excitation axis. In addition, the curves are symmetrical with respect to $Z = 0$, due to the fact that the loops are symmetric with respect to the rotation axis which is parallel to that of the source ($\xi = 0$) as shown in Figure 6(b).

One could point out that the positive effect of the coil’s size on the induced measured quantity is greater when the excitation field is stronger (larger differences between the three curves in the vicinity of $Z = 0$). It is also remarkable that the induced voltage is exponentially dependent on the distance between the thin closed wire and the source current, which is indicated not only by the decrease for large $|Z|$ in Figure 6(a) but with the increase for large $X$ in Figure 5(a) as well.

5. Conclusions

The case of a metallic loop of arbitrary shape rotated with respect to an arbitrary axis in the presence of an infinite dipole is investigated. The induced voltage is evaluated rigorously via transformation relations and the derived formula can be easily generalized to treat any
kind of axial excitation. The time dependence of the measured voltage is of sinusoidal form only if the shape of the loop combined with the rotation axis is symmetric. Additionally, the intuitive guess that the size of the loop, affects positively the inductive action is verified by the numerical results. The distance between the source and the loop is also found to reduce the measured voltage along the coil. As far as the rotation axis is concerned, the most substantial response has been recorded when it is normal to the axis of the dipole current, a result that can have technical applicability.

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