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Effect of Cobalt Dopants on Magneto-Optic Conversion of Magnetite Nanostructures

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Abstract
In this research, the effect of rapid heating process on the magneto-optic conversion of the Co-doped Fe_3O_4 nanostructures prepared by the co-precipitation method is introduced. The variation of relative magnetization of these nanostructures were determined as a function of heating temperature in case these nanostructures are not irradiated with intensive light (laser) and then in case of irradiated with laser to determine the efficiency of magneto-optic conversion. Also, the relative magnetization of these nanostructures was determined as a function of the doping level with cobalt in the Fe_3O_4 nanostructures. Results showed that both light irradiation and doping level have reasonable effects on the magneto-optic conversion characteristic that may serve the practical applications of these ferromagnetic materials.

Keywords: Magnetite; Nanostructures; Magneto-optic conversion; Ferromagnetic materials
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1. Introduction

Magneto-optic conversion involves the interaction between magnetic fields and light, enabling the modulation of optical properties such as polarization or intensity [1]. This effect is often realized using the Faraday Effect, where light passing through a magneto-optic material experiences a rotation in polarization proportional to the applied magnetic field [2]. Magneto-optic conversion finds applications in various fields, including telecommunications, where it is used in optical isolators and modulators [3]. It is also crucial in data storage, enabling magneto-optical disks for high-density storage [4]. Additionally, it is employed in sensors for precise magnetic field measurement and in advanced optical devices like quantum computing and laser systems [5].

Magnetite (Fe_3O_4) is a naturally occurring iron oxide with both ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions, making it a mixed-valence compound [6,7]. It has magnetic properties, being one of the few naturally magnetic minerals, and is often used in a variety of applications [8]. Magnetite is crucial in the production of steel and as a catalyst in various chemical processes. In biomedicine, it is used in magnetic resonance imaging (MRI) and as a carrier for targeted drug delivery [9]. Additionally, magnetite nanoparticles are employed in environmental applications such as water purification and in energy storage systems like lithium-ion batteries [10-12].

Cobalt doping in magnetite (Fe_3O_4) significantly influences its magneto-optic properties, enhancing the material's ability to interact with light in the presence of a magnetic field [13]. By substituting iron (Fe) atoms with cobalt (Co), the electronic structure and magnetic properties of the material are modified, leading to an increase in magnetization and spin-orbit coupling [14,15]. This alteration enhances the Faraday effect, which is crucial for magneto-optic applications like optical isolators and magneto-optic sensors [16]. Additionally, cobalt doping can shift the absorption spectrum, improve the coercivity, and increase the sensitivity of magnetite, making it a promising material for advanced magneto-optic devices [17-20].

The solid-state reaction method is widely used for doping iron oxides with ferromagnetic metals to enhance their magnetic properties [21]. In this process, metal salts or oxides of ferromagnetic elements, such as cobalt, nickel, or manganese, are mixed with iron oxide (Fe_2O_3 or Fe_3O_4) powders [22]. The mixture is then heated at high temperatures in a controlled atmosphere, typically in a furnace, to promote chemical reactions and facilitate the diffusion of the dopant into the iron oxide lattice [23]. This method results in the formation of doped iron oxide materials with improved magnetic, electrical, and structural properties, making them suitable for various technological applications [24-26].

In this research, the effect of self-absorption by the active medium molecules on the output power characteristics of a locally manufactured, low-pressure CW CO_2 laser was discussed.

2. Experimental Part

To prepare cobalt-doped magnetite (Co-doped Fe_3O_4) nanostructures grown on ceramic substrates (SiO_2) and rapidly heat them for magnetization measurements, as shown in Fig. (1), the experimental procedures will be presented.

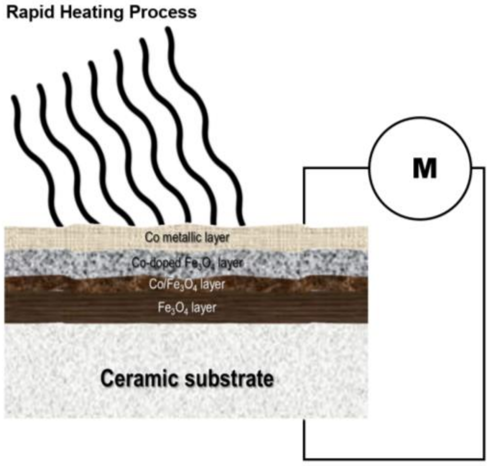

Fig. (1) Schematic diagram of measuring magnetization of Co-doped Fe_3O_4 nanostructures subjected to rapid heating process

There are several methods to synthesize Co-doped Fe_3O_4 nanostructures, with co-precipitation method being the most common for high-quality thin films and nanostructures. In co-precipitation method, iron salts (such as $FeCl_3$) and cobalt salts (e.g., $CoCl_2$) are dissolved in deionized water, adjusting the ratio of cobalt to iron to achieve the desired doping level (typically between 1-10 mol% Co). A solution of sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH) is prepared to control the pH, and slowly add it to the iron-cobalt solution while stirring. This will induce the precipitation of Fe_3O_4 and Co-doped Fe_3O_4 particles. Stirring continues for several hours to ensure uniform precipitation. Filter the precipitate and wash it with distilled water to remove any residual salts. After filtration, the precipitate can be dried at low temperatures (around 50-80°C) for several hours.

For the co-precipitation method, annealing of the resulting nanoparticles at temperatures between 500–800°C can be used to enhance crystallinity and ensure formation of magnetite (Fe_3O_4) phase.

After the cobalt-doped magnetite nanostructures are synthesized, the sample must be rapidly heated to measure magnetization as a function of temperature. The ceramic substrate with the nanostructures is placed in a high-temperature furnace or a rapid thermal annealing (RTA) system. Rapid heating (with heating rates of up to 10^4 °C/s) is applied to quickly increase the temperature to the desired value (typically ranging from 300–900°C, depending on the study objectives). During this rapid heating process, ensure that the heating system is coupled with a temperature monitoring and feedback system for precise control.

To measure the magnetization, the sample is placed in a vibrating sample magnetometer (VSM) or a superconducting quantum interference device (SQUID) magnetometer. The temperature of the sample can be controlled using a cryostat or a heating unit. A varying external magnetic field is applied to the sample while simultaneously monitoring the induced magnetization as a function of temperature and field. The results can reveal information on the magnetic properties of the Co-doped magnetite nanostructures, including saturation magnetization, coercivity, and the transition from ferromagnetic to superparamagnetic behavior.

3. Results and Discussion

The behavior of the relative magnetization of Co-doped Fe_3O_4 nanostructures as a function of heating temperature demonstrates distinct magnetic property changes without light irradiation. Initially, at a low heating temperature (around 0°C), the relative magnetization is relatively low, at 0.5. This could be due to the dominance of superparamagnetic behavior in the nanostructures, where the magnetic moments are disordered and unable to fully align with the external magnetic field at room temperature.

As the temperature rises to 200°C, the relative magnetization increases to 0.58, suggesting that the thermal energy is sufficient to facilitate the alignment of the magnetic moments, thus enhancing the magnetization. This may be due to the onset of ferromagnetic ordering or an increase in crystallinity and structural ordering within the Co-doped Fe_3O_4 phase, which can strengthen the magnetic properties [27]. However, as the temperature continues to rise beyond 200°C, the relative magnetization begins to gradually decrease. By 700°C, the relative magnetization reaches 0.2. This reduction could be attributed to the high temperatures causing thermal agitation, which may lead to the disruption of the magnetic ordering or the onset of phase transitions that weaken the overall magnetization. Additionally, the possible oxidation or breakdown of the Fe_3O_4 structure at elevated temperatures may contribute to the decreased magnetization [28,29].

When a light is used to irradiate the prepared sample when the relative magnetization is measured with increasing heating temperature, it was observed that the relative magnetization is drastically increased to reach 3 but sharply decreasing with increasing heating temperature to coincide with the former case at approximately 500°C.

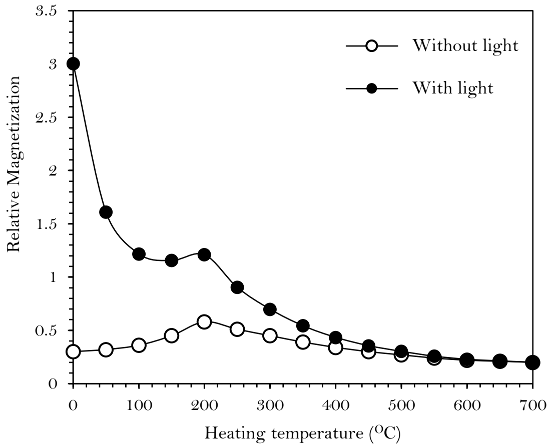

Fig. (2) Variation of relative magnetization of the Co-doped Fe_3O_4 nanostructures with heating temperature with and without light irradiation

The relative magnetization was also measured as a function of percentage doping level with cobalt (5-35%) in the Fe_3O_4 nanostructures. The relative magnetization increases with the initial increment in the doping level to reach a maximum of 3 at doping level of 25%, which is considered high level. However, the matching and alignment of magnetic dipoles in both cobalt and magnetite support the magnetization of the structure [29,30]. Further increment in the doping level beyond 25% causes to decrease the relative magnetization due to the dominant magnetization of cobalt dopants with the magnetite structure as they occupy the sites of Fe^{3+} in the Fe_3O_4 lattice and convert the lattice structure to Co_3O_4, which gradually show reciprocal alignment [31-33].

4. Conclusion

In concluding remarks, both light irradiation and doping level have reasonable effects on the magneto-optic conversion characteristic that may serve the practical applications of these ferromagnetic materials. The relative magnetization was increased by 1000% when a laser beam is used to irradiate the structure. However, the effect of laser irradiation is vanished at heating temperature of 500°C to be similar to the case of non-irradiation. Also, increasing the doping level 5 times has led to double the relative magnetization before starting to decrease at higher levels of doping.

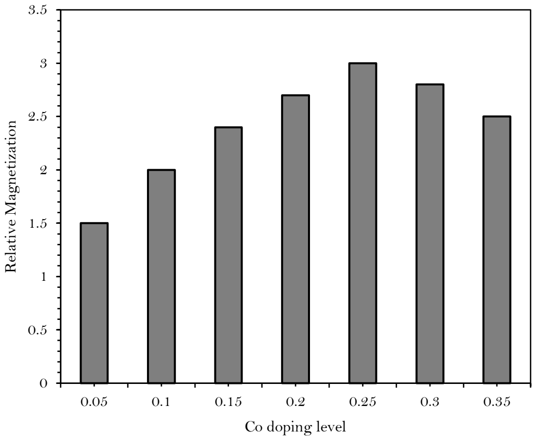

Fig. (3) Variation of relative magnetization of the doping level of Co in Fe_3O_4 nanostructures

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