Tunable diffraction of magnetic fluid films and its potential application in coarse wavelength-division multiplexing

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Received February 27, 2004

When an external magnetic field is applied parallel to the film surface of a magnetic fluid film, a high-quality one-dimensional periodic chain structure is formed when the field strength reaches a certain level. With a periodic chain structure in the magnetic fluid film, an incident light is diffracted onto the magnetic thin film. The results show that the one-dimensional periodic chain structure in the magnetic fluid film can serve as an optical grating. Further investigations reveal the feasibility of developing tunable coarse wavelength-division multiplexing by utilizing a periodic chain structure. © 2004 Optical Society of America

OCIS codes: 160.3820, 260.3160, 230.1950.

As a result of the agglomeration of magnetic particles, many types of structural pattern, such as a disordered column structure,[1,2] a two-dimensional hexagonal structure,[3,4] and a column splitting state,[4] are formed in magnetic fluid films when an external magnetic field is applied perpendicularly to a film surface. A number of published papers have shown that the structural patterns can be manipulated by adjustment of the control parameters.[5,6] Some research has also discussed relevant physical interactions in these tunable structural patterns.[4,7,8] Because of the versatility of these tunable structures, magnetic fluid films under perpendicular fields exhibit many optical properties, such as tunable transmission,[9,10] a tunable refractive index,[11] and magnetochromatics.[3,12] These particular optical characteristics of magnetic fluid films show promise for the development of photonic devices such as tunable optical attenuators, optical modulators, switches, filters, and photonic crystals.[13]

When an external magnetic field is applied parallel to the film surface, a randomly distributed chain structure is obtained in a magnetic fluid film.[14–16] Many researchers have pointed out that the magnetic chains are optically anisotropic,[10,14–16] and hence birefringence or dichroism is generated for magnetic fluid films. With the recent success in the formation of a high-quality one-dimensional periodic chain structure in a magnetic fluid film under parallel fields, new optical effects can be generated. In this Letter we explore the diffraction behavior of a one-dimensional periodic chain structure in a magnetic fluid film under parallel magnetic fields and study the feasibility of a tunable wavelength demultiplexer by using the diffraction effect.

The magnetic fluid used here is kerosene-based $MnFe_2O_4$. To obtain a film we inject the fluid into a rectangular cell with an area of 10 μm $\times$ 1000 μm and a depth of 0.3 μm on a glass plate. The magnetic fluid film is then covered with another glass plate and put into a Helmholtz coil that provides a uniform magnetic field parallel to the film surface. The structural patterns in the film were observed by use of an optical microscope and a CCD. Thus the structural images could be recorded and analyzed. For investigation of the diffraction effect of the magnetic fluid film under parallel fields, a parallel white light is normally incident upon the film. The transmitted light is monitored with a CCD, and its spatial intensity distribution is probed by feeding the transmitted light into a spectrometer and a photomultiplier.

When an external magnetic field H is applied parallel to the surface of a magnetic fluid film, magnetic particles in the magnetic fluid film start to agglomerate to form a one-dimensional periodic magnetic-chain structure as the field strength exceeds a certain value. A typical one-dimensional periodic chain structure in a magnetic fluid film under a magnetic field ($H =$ 150 Oe) is shown in Fig. 1. Chain width a and chain spacing Δx (i.e., the period of the structure) were 1.2 and 2.32 μm, respectively.

We investigate the diffraction effect of the ordered structure shown in Fig. 1 by use of a parallel white light that is normally incident upon the magnetic film, as shown in Fig. 2. The image of the transmitted

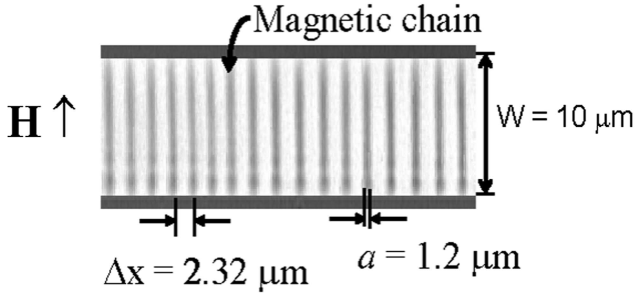

Fig. 1. One-dimensional periodic chain structure in the magnetic fluid film under a parallel magnetic field. The concentration M_s of the fluid is 15.5 emu/g, the film thickness L is 0.3 μm, the width of the cell, W, is 10 μm, the applied field strength H is 150 Oe, and the sweep rate of applying the field is 10 Oe/s.

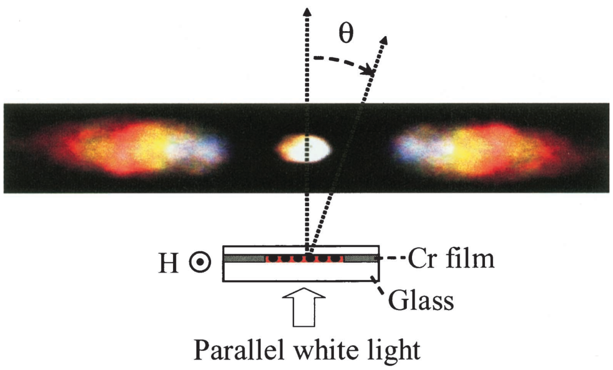

Fig. 2. Schematic cross section of the magnetic fluid film possessing a one-dimensional periodic chain structure and a diffracted image of the transmitted light through the film. Each black dot in the schematic represents the cross section of a magnetic chain. The Cr film shown here blocks the incident light outside the cell. The parallel white light is normally incident upon the film. The white spot at the center of the diffracted image is located at a certain distance above the film and is in the normal line of the film. Angle θ denotes the diffracted angle of the transmitted light.

light is shown in Fig. 2. The white spot was found at the center of the image along the normal (incident) line of the film (incident) light. In addition, colorful images were obtained on both sides of the white spot. Note that a color sequence from purple to red resulted along directions outward from the white spot. According to the image of the transmitted light shown in Fig. 2, the white spot corresponds to the zeroth-order diffracted light, and the colorful parts are of the first-order diffraction for various wavelengths of visible light. This color sequence is attributed to the fact that the wavelength of purple light is the shortest whereas that of red is the longest in visible light.

To identify the diffracted angle of the first-order diffraction for a given wavelength λ, say, 600 nm, we detected the spatial intensity distribution, shown in Fig. 3, in which angle θ is the span from the normal line of the film to the detected point. It was found that the first-order diffraction peaks are located at $\theta_{\text{exp}} = \pm 15.00°$. We then used the grating equation

$$\Delta x \sin \theta_{\text{th}} = n\lambda \tag{1}$$

to calculate the theoretical value of the first-order diffraction angle θ_{th} for $\lambda = 600$ nm in the case where n is 1 for the first-order diffraction. With $\Delta x = 2.32$ μm from Fig. 1, θ_{th} is 14.99°, which is consistent with the experimental angle, θ_{exp}. Consistency between θ_{th} and θ_{exp} was also found for other wavelengths. Therefore the one-dimensional periodic chain structure in a magnetic fluid film under a parallel magnetic field is an optical grating.

According to the diffraction image shown in Fig. 2, the first-order diffraction angles of various wavelengths are different. This reveals that the one-dimensional chain structure is able to split light with different wavelengths. A significant application that can be achieved by use of this property is wavelength-division multiplexing. Here we lay out the potential for using a tunable one-dimensional periodic chain structure in a magnetic fluid film for tunable coarse wavelength-division multiplexing (CWDM).

To fulfill the requirements of CWDM, the device should be able to resolve two lights with wavelengths that differ by 20 nm. To test this ability, we scanned the spatial intensity distributions of the first-order diffraction peaks of various wavelengths (580, 600, 620, and 640 nm), and the results are plotted in Fig. 4. These four peaks are clearly resolvable.

From Eq. (1) the peak separation between two first-order diffractions of various wavelengths λ_1 and λ_2 can be calculated as

$$\Delta\theta_p = \theta_{\text{th},\lambda 1} - \theta_{\text{th},\lambda 2} = \sin^{-1}(\lambda_1/\Delta x) - \sin^{-1}(\lambda_2/\Delta x)\,, \tag{2}$$

where $\theta_{\text{th},\lambda 1}$ and $\theta_{\text{th},\lambda 2}$ are the calculated first-order diffraction angles for λ_1 and λ_2, respectively. Experimentally, Δx in Eq. (2) becomes smaller under a higher field. Thus $\Delta\theta_p$ should increase. Figure 5 illustrates the experimental observation of the increase

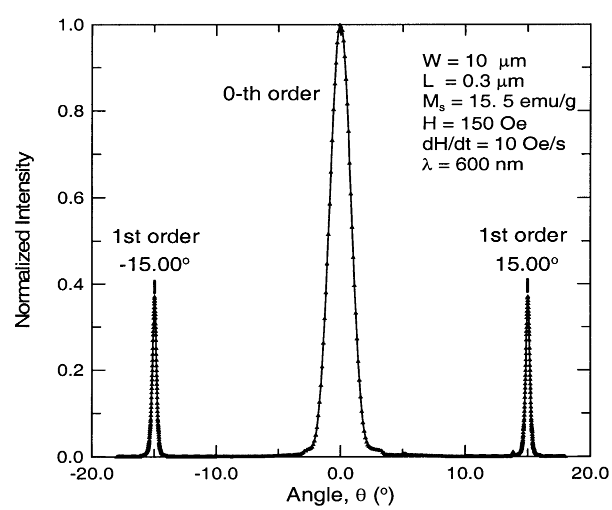

Fig. 3. Spatial intensity distribution of the diffracted light with a wavelength of 600 nm.

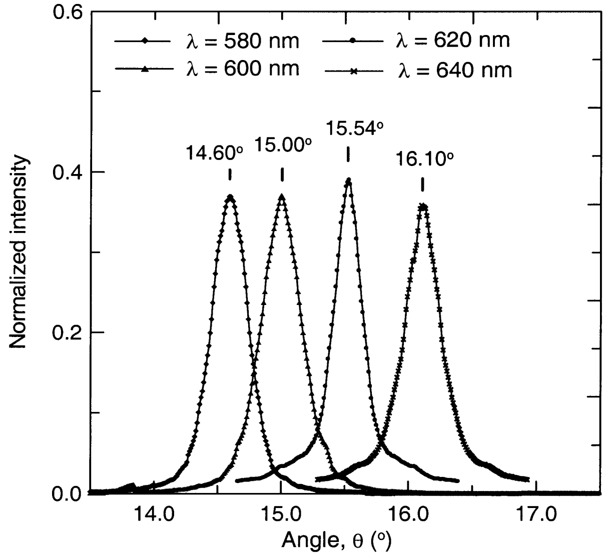

Fig. 4. Spatial intensity distributions of the first-order diffraction peaks for various wavelengths λ. The concentration of the fluid (M_s) is 15.5 emu/g, the film thickness (L) is 0.3 μm, the width of the cell (W) is 20 μm, the applied field strength (H) is 150 Oe, and the sweep rate of the field application is 10 Oe/s.

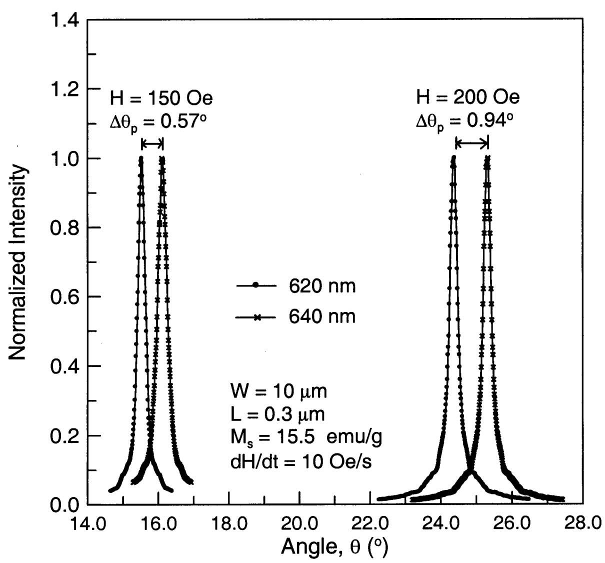

Fig. 5. Spatial intensity distributions of the two first-order peaks of the diffracted light with wavelengths of 620 and 640 nm under 150 and 200 Oe, respectively. The separation $\Delta\theta_p$ between the two peaks is increased from 0.57° to 0.94° when the field H increases from 150 to 200 Oe.

in $\Delta\theta_p$ when the field strength is increased. $\Delta\theta_p$ was 0.57° under 150 Oe, whereas $\Delta\theta_p$ increased to 0.94° under 200 Oe. The variation in $\Delta\theta_p$ with changes in field strength definitely demonstrates the tunability of CWDM through the use of a one-dimensional periodic structure in a magnetic fluid film under parallel magnetic fields.

In conclusion, the one-dimensional periodic chain structure in a magnetic fluid film under parallel magnetic fields acts as an optical grating. It has further been demonstrated that the resolution of the wavelength division of the optical grating satisfies the requirements of CWDM. With the tunability of the periodic chain structure, one can tune the characteristics of magnetic-fluid CWDM by adjusting the external field strength.

This work was supported by the National Science Center of the Republic of China (ROC) under grant NSC92-2112-M-003-010 and NSC92-2112-E-212-011 and was partially supported by the Ministry of Education of the ROC under grant 91-N-FA01-2-4-2. H.-E. Horng's e-mail address is phyfv001@scc.ntnu.edu.tw.

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