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SHORT COMMUNICATION

Microsecond-scale switching time of magnetic fluids due to the optical trapping effect in waveguide structure

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Abstract Instead of the conventional method of monitoring the transmitted light through a ferrofluid film, in this study we use ferrofluids as the guiding layer in a double metal-cladding optical waveguide structure, and measure the reflected light intensity to investigate the chain formation speed (switching speed) in ferrofluids. We conclude that the ultrahigh-order mode-induced optical trapping effect may be the main reason for the observed fast switching time which is increased by at least three orders of magnitude when a magnetic field was applied.

Keywords Ferrofluids · Optical waveguide · Optical trapping effect

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1 Introduction

Ferrofluids, also known as magnetic fluids have generated diverse scientific interests,such as typical dipolar fluids, self-assembled soft materials (Safran 2003), and pattern-forming systems (Pi et al. 2000). On the other hand, such fluids find uses in many areas, such as magnetic sealing, information storage media, magnetic refrigeration (Suslick et al. 1996), and various applications in the biomedical field (Kim et al. 2006; McCloskey et al. 2003). Although this field has been investigated intensively for decades, many distinct and often unexpected properties can still occur. For example, in spite of general beliefs, unambiguous experimental evidence has been presented that the Kelvin force breaks down when applied to ferrofluids (Odenbach and Liu 2001).

A key issue in research on ferrofluids is the structure formation and the corresponding phase behavior under external magnetic field. Recently, direct observation of dipolar chains in homogeneous magnetic field has been obtained by cryogenic electron microscopy (Butter et al. 2003; Klokkenburg et al. 2006). However, the mechanisms governing the dynamics are still ambiguous, which cause the research on the response time of chain formation play an important role on the further application. A number of reports have pointed out that the agglomeration rate of magnetic nanoparticles is usually in second scale (Deng et al. 2008; Horng et al. 2004; Dai et al. 2010) or even in minute scale (Li et al. 2007, 2002, 2004). In addition, it is also demonstrated that a finite retardation exists between the switch on/off of the external field and the variation of the transmission through the ferrofluid films, and this corresponding retarding time ranges from several to tens of milliseconds, depending on the field strength (Yang et al. 2004).

It is well known that with the help of a high numerical aperture (NA) objective lens, particles with sizes ranging from nanometers to micrometers will be three dimensionally trapped by optical tweezers (Ashkin et al. 1986, 1987). Recently, it was reported that hundreds of microparticles can be simultaneously trapped in a regular array by means of producing an optical lattice even without adopting an external optical projection lens configuration (Sun et al. 2007a, b). Inspired by this fascinating idea, we take a quite simple approach in which the ferrofluids are sealed in a double metal-cladding optical waveguide (DMCW) structure of millimeter scale, where the ultrahigh-order modes can be excited at small incident angle (Lu et al. 2004; Wang et al. 2008; Yu et al. 2008). Theoretically, the magnetic nanoparticles will be optically trapped regularly inside the sample room via the periodic intensity pattern of the excited ultrahigh-order mode. Our experimental results demonstrate a switching time less than 2 ms, which is less by three orders of magnitude than that observed in a single ferrofluids film. In addition, the retarding time is also found to be faster by two orders of magnitude faster. This study may provide a deeper insight in dipolar fluids in general, and is extremely important for various practical applications.

2 Experiment and results

The schematic diagram of the DMCW in this experiment is illustrated in Fig. 1. With a relative thick gold film (about 300 nm) deposited on the upper side of a glass substrate, a glass cell of 5 mm in radius and 0.7 mm in depth works as the sample room, and a thin silver film (about 30 nm) is coated on the top side of a glass slab (0.3 mm), which acts as the coupling layer. In the present investigation, the density of the magnetic fluid and nanoparticle are 1.20 g/ml and 5.18 g/cm^3, respectively, and the mass of particles per volume fraction is 0.248 g/ml. The water-based Fe_3O_4 magnetic fluid samples were provided by Anhui Jingke Magnetic Liquids Co. Ltd., and the distribution of magnetic nanoparticles' sizes ranges between 8 and 12 nm and follows the normal distribution the central size of which is 10 nm. In our experiment, the ferrofluids with the volume fraction 0.032% were injected into the sample room, and so the DMCW is actually composed of four layers among which the ferrofluid film and the thin glass slab function as the guiding layers, while the two metal films serve as the cladding layers.

When a laser beam is incident upon the DMCW structure with a very small fixed angle, ultrahigh-order modes will be excited under the matching condition by the free-space coupling technology (Li et al. 2003). As shown in Fig. 2, the intensity of the reflected beam varies with the incident angle and forms a serial of sharp dips in the reflection spectrum, which indicates the energy coupling of the light source to the ultrahigh-order modes (Lu et al. 2004; Wang et al. 2008; Yu et al. 2008). Since the resonance dip position is very sensitive to the refractive index of the guiding layer, a minute variation in the refractive index of the ferrofluids will cause an angular shift of the resonance dip. As a result, an intensity variation of the reflected beam can be observed at a fixed incident angle. The inset of Fig. 2 shows that the mode density of ultrahigh-order modes is decreasing in the limit of small incident angle, which makes it possible to excite a pure ultrahigh-order mode. Also, in order to achieve a good linearity and high sensitivity, the operation incident angle is selected at the middle area of the falling edge or rising edge. It is also well established that the refractive index of the ferrofluid films becomes higher under external magnetic fields (Yang et al. 2002; Chen et al. 2003), and so the intensity variation of the reflected beam can be magnetically controlled. Attributed to the application of negative dielectric coefficient materials (metals) and a thick guiding layer, sensors with DMCW structure are completely different from that with conventional waveguide and the surface plasmon resonance (SPR) structure in which the sample under test is always located in the evanescent field region. Since our structure contains the ferrofluids in the guiding region that supports the oscillating field, a significant sensitivity enhancement due to the strong concentration of the electromagnetic field is exhibited (Lu et al. 2004; Wang et al. 2008).

A uniform magnetic field *H,* in *y* direction (as shown in Fig. 1) is applied parallel to the film surface and

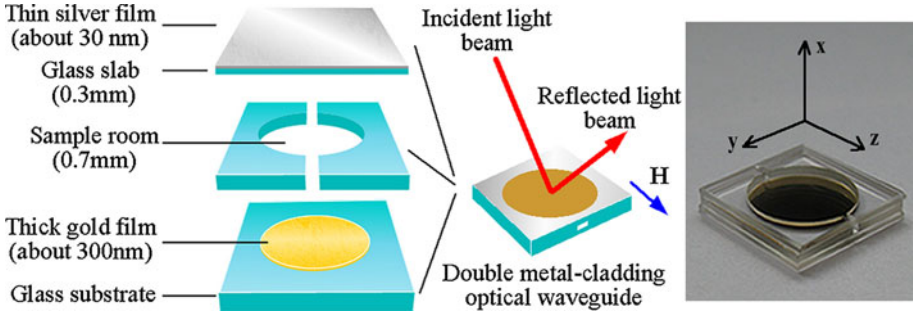

Fig. 1 Schematic layout of the double metal-cladded optical waveguide

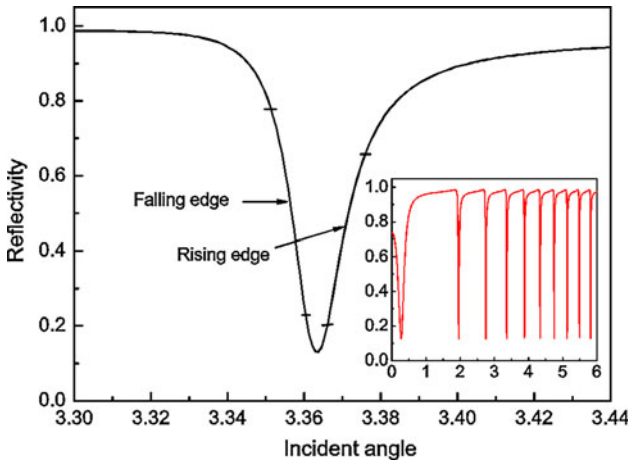

Fig. 2 Reflection spectrum of the ultrahigh-order modes in the DMCW structure with parameters $\lambda = 840$ nm, $\varepsilon_{\text{metal}} = -17.3 + 0.68i$, $\varepsilon_{\text{guiding\_layer}} = 1.8$, $d_{\text{coupling\_layer}} = 36$ nm, and $d_{\text{guiding\_layer}} = 1$ mm (*inset* the reflectivity for the case of incident angle range from 0 to 6 degree)

perpendicular to the incident light beam. We used 850 nm continuous wave lasers (Toptica Photonics, DL 100) of 100 mW in power in our experiments and used HT100G Gauss meter provided by Shanghai Hengtong Magneto Electric Technology Co. Ltd., to measure the magnetic field. In Fig. 3, the time-dependent reflectivity is normalized with respect to that obtained without the magnetic field R_0. Here, the incident angle is set at 3.67°, which is at the middle area of the rising edge. It was found in Fig. 3a that the reflectivity decreases quickly to a lower level in less than 1.2 ms when the field about 125 Oe is switched on, and rises to R_0 in less than 0.9 ms when the field is switched off. Figure 3b shows that when the modulation period of the magnetic field is prolonged to 4 s, the reflectivity remains nearly unchanged until the magnetic field is withdrawn. Based on the experimental results, the corresponding switching time is reduced by three orders of magnitude shorter than those reported in the literature (Horng et al. 2004). However, in Fig. 3c, the switching times increase dramatically as the source is replaced by a confocal laser beam, which we shall explain later.

We also carried out experiments to investigate the intensity variations of the reflected beam upon simply turning on/off the laser source. As can be seen in Fig. 4, the laser was turned on and off twice, while the incident angle is fixed at the middle of a falling edge without any external magnetic field. It can be seen that (1) there is an increase ($\Delta R = R_{\text{off}} - R_{\text{on}}$) in the reflectivity when the laser was switched on, and (2) the reflectivity gradually declines to the stable level R_{on} within about 7 s. Similar phenomenon can also be observed at the rising edge, and all these processes can be stably repeated. To the best of our knowledge, no such phenomenon has been reported for a single

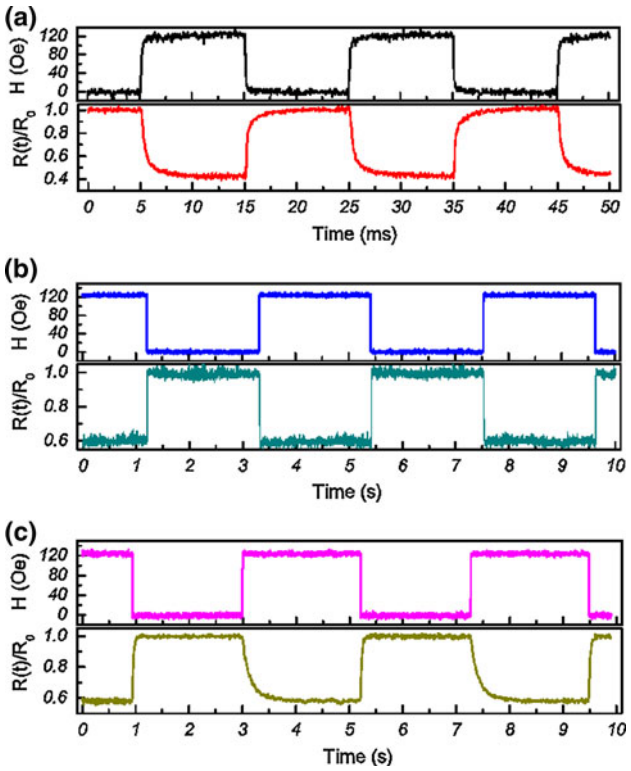

Fig. 3 Periodically applied magnetic fields and the corresponding dynamic variations of the normalized reflectivity. **a** The modulation period of the magnetic field is 20 ms. **b** The modulation period of the magnetic field is 4 s. **c** The modulation period of the magnetic field is 4 s and a confocal laser beam is applied instead of the parallel laser beam

ferrofluid film structure. We conclude that the relaxation behavior is an evidence of the magnetic nanoparticles being redistributed under the light beam-induced field, which is responsible for the rapid switching speed when external magnetic field is applied.

Since the illustrated switching time is even smaller than the reported retarding time (Yang et al. 2004), we measured the corresponding retarding time of the proposed structure when the incident angle is fixed at the middle of a falling edge of the reflection spectrum. As can be seen from Fig. 5, the time-dependent reflectivity also exhibits the retarded effect upon the switching on/off of the external field. The retarding time to the switching-on of the magnetic field is about 0.06 ms, while the retarding time to the switching-off of the magnetic field is about 0.01 ms. Both these times are faster than that reported in a single ferrofluids film by two orders of magnitude.

3 Theory and discussion

To understand the physics behind the above phenomenon, we numerically calculated the time-averaged z-component

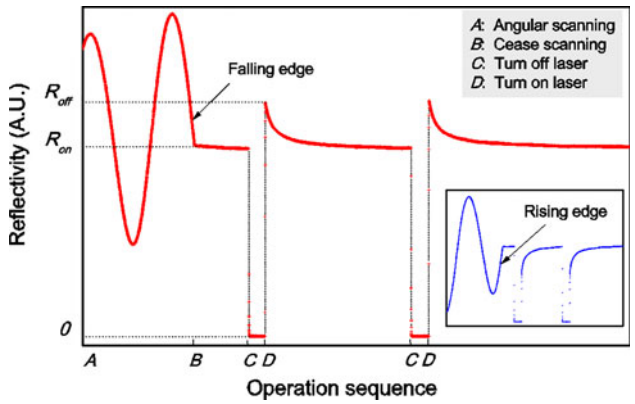

Fig. 4 The reflectivity sequence obtained by angular scanning and switching on and off the laser source. The incident angle is at the middle of a falling edge (*inset* The incident angle is at the middle of a rising edge)

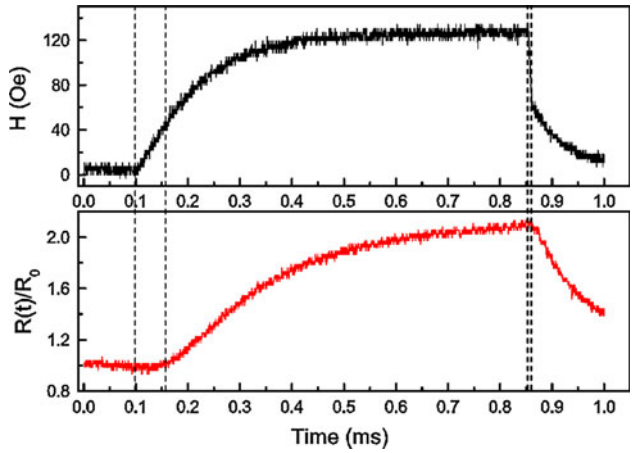

Fig. 5 Time dependencies of the applied magnetic pulse and the normalized reflectivity. The operation incident angle is selected at a falling edge

of the Poynting vector, S_z, of a pure ultrahigh-order mode (Fig. 6), by the characteristic matrix method (Born et al. 1999). The amplitude of S_z in the guiding layer is enhanced by 68 times than that in the air before coupling into the DMCW structure. As was pointed out by Deng et al. (2008), Horng et al. (2004), Dai et al. (2010), the clustering of magnetic nanoparticles will be resolved at large power densities and resulting in a rapid agglomeration when an external field is applied. However, as will be clarified later, apart from high energy density, large-scale optical trapping effect inside the guiding layer may be the primary reason for the rapid agglomeration of nanoparticles.

Figure 6 shows the electromagnetic energy distribution for an ultrahigh-order mode which oscillates periodically in space along x axis. Besides, the excited ultrahigh-order mode propagates in z direction in the guiding layer, leading to the periodic-distributed electromagnetic energy along the z axis, where the oscillating period is determined by the

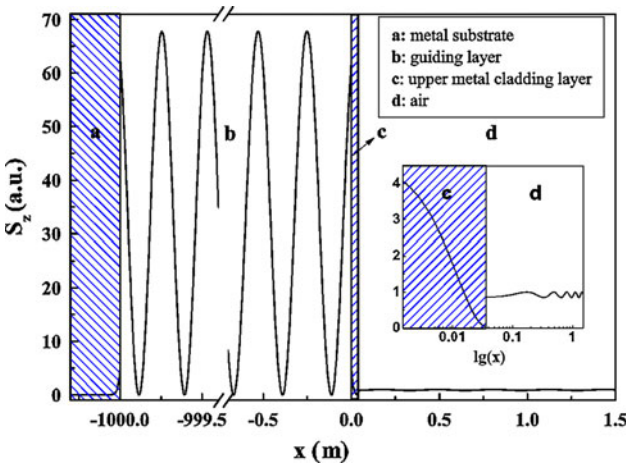

Fig. 6 Plot of z-component of the Poynting vector of a pure ultrahigh-order mode with parameters $\varepsilon_{metal} = -17.3 + 0.68i$, $\lambda = 632.8$ nm, $\varepsilon_{guiding\_layer} = 1.8$, $d_{coupling\_layer} = 36$ nm, $d_{guiding\_layer} = 1$ mm, and $\theta = 2.56°$. The maximum of the Poynting vector in air is normalized to unit (*inset* close-up view for the Poynting vector in the upper metal-cladded layer and air)

propagation constant, β, of the excited mode (Yuan et al. 2011). Thus, in the x–z plane, the mode field pattern can be simplified as a checkerboard-like optical lattice (as shown in Fig. 7). Since simultaneous trapping of hundreds of particles of micrometer size in a regular array is possible even without adopting an external optical projection lens configuration and even when these microparticles are under an external driving force in the laminar flow (Sun et al. 2007a, b), there is no doubt that the particles of nanometer size within the excited mode field will all be optically trapped.

As seen in Fig. 7, the nanoparticles are trapped two dimensionally in x–z plane and distributed homogeneously along the y direction, thus the column-like structure of nanoparticles parallel to the magnetic field has already

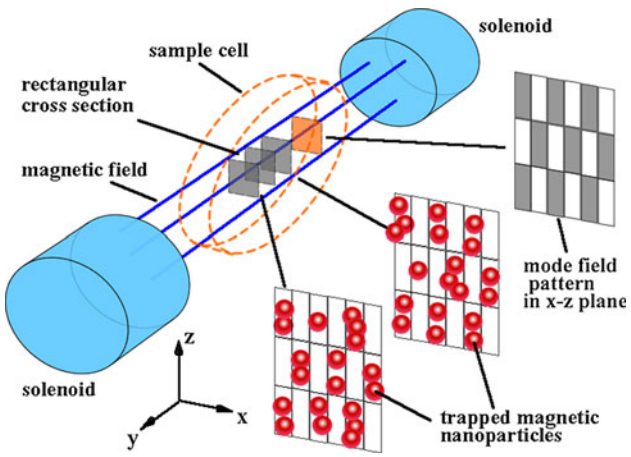

Fig. 7 Plot showing the optically trapped magnetic nanoparticles in the sample room

been formed before the field is switched on. Consequently, when the external magnetic field is switched on, these nanoparticles in the sample room simply need to rotate to align their magnetic moment to the field direction and form nanoparticle chains, resulting in a fast switching speed. The only difference between the use of a parallel laser beam and that of a confocal laser beam is the energy distribution in the sample cell. Since more than one ultrahigh-order modes in the guiding layer can be excited by a confocal laser beam, the periodical structure of the electromagnetic energy distribution along the x direction is significantly disrupted. Experimental results in Fig. 3c show that the switching time is increased by three orders of magnitude simply, when energy distribution along the x direction is changed. This result confirms the conclusion that the optical trapping effect is the main reason for the observed fast switching speed.

4 Conclusion and future works

In conclusion, we proposed in this study a new DMCW structure in which the ferrofluid films serve as the guiding layer. Great enhancements of both the switching speed (agglomeration rate of the magnetic nanoparticles) and the retarding time are observed. The physical mechanism responsible for the enhancements is clarified, and the effect of optical trapping due to ultrahigh-order modes is addressed. Our attention will be focused on the future studies concerning the influence of beam polarization.

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References

Ashkin A, Dziedzic J, Bjorkholm J, Chu S (1986) Observation of a single-beam gradient force optical trap for dielectric particles. Opt lett 11(5):288–290

Ashkin A, Dziedzic J, Yamane T (1987) Optical trapping and manipulation of single cells using infrared laser beams. Nature 330(6150):769–771

Born M, Wolf E, Bhatia AB (1999) Principles of optics: electromagnetic theory of propagation, interference and diffraction of light. Cambridge University Press, Cambridge

Butter K, Bomans P, Frederik P, Vroege G, Philipse A (2003) Direct observation of dipolar chains in iron ferrofluids by cryogenic electron microscopy. Nat Mater 2(2):88–91

Chen Y, Yang S, Tse W, Horng H, Hong CY, Yang H (2003) Thermal effect on the field-dependent refractive index of the magnetic fluid film. Appl phys lett 82(20):3481–3483

Dai Q, Deng H, Zhao W, Liu J, Wu L, Lan S, Gopal A (2010) All-optical switching mediated by magnetic nanoparticles. Opt Lett 35(2):97–99

Deng H, Liu J, Zhao W, Zhang W, Lin X, Sun T, Dai Q, Wu L, Lan S, Gopal A (2008) Enhancement of switching speed by laser-induced clustering of nanoparticles in magnetic fluids. Appl Phys Lett 92:233103

Horng H, Chen C, Fang K, Yang S, Chieh J, Hong C, Yang H (2004) Tunable optical switch using magnetic fluids. Appl Phys Lett 85:5592

Kim J, Lee J, Lee J, Yu J, Kim B, An K, Hwang Y, Shin C, Park J (2006) Magnetic fluorescent delivery vehicle using uniform mesoporous silica spheres embedded with monodisperse magnetic and semiconductor nanocrystals. J Am Chem Soc 128(3):688–689

Klokkenburg M, Erné B, Meeldijk J, Wiedenmann A, Petukhov A, Dullens R, Philipse A (2006) In situ imaging of field-induced hexagonal columns in magnetite ferrofluids. Phys Rev Lett 97(18):185702

Li J, Zhao B, Lin Y, Qiu X, Ma X (2002) Transmission of light in ionic ferrofluid. J Appl Phys 92:1128

Li H, Cao Z, Lu H, Shen Q (2003) Free-space coupling of a light beam into a symmetrical metal-cladding optical waveguide. Appl Phys Lett 83:2757

Li J, Liu X, Lin Y, Qiu X, Ma X, Huang Y (2004) Field-induced transmission of light in ionic ferrofluids of tunable viscosity. J Phys D Appl Phys 37:3357

Li J, Liu X, Lin Y, Bai L, Li Q, Chen X, Wang A (2007) Field modulation of light transmission through ferrofluid film. Appl Phys Lett 91:253108

Lu H, Cao Z, Li H, Shen Q (2004) Study of ultrahigh-order modes in a symmetrical metal-cladding optical waveguide. Appl Phys Lett 85(20):4579–4581

McCloskey K, Chalmers J, Zborowski M (2003) Magnetic cell separation: characterization of magnetophoretic mobility. Anal Chem 75(24):6868–6874

Odenbach S, Liu M (2001) Invalidation of the Kelvin force in ferrofluids. Phys Rev Lett 86(2):328–331

Pi H, Park S, Lee J, Lee K (2000) Superlattice, rhombus, square, and hexagonal standing waves in magnetically driven ferrofluid surface. Phys Rev Lett 84(23):5316–5319

Safran S (2003) Ferrofluids: magnetic strings and networks. Nat Mater 2(2):71–72

Sun Y, Bu J, Ong L, Yuan X (2007a) Simultaneous optical trapping of microparticles in multiple planes by a modified self-imaging effect on a chip. Appl Phys Lett 91:051101

Sun Y, Yuan X, Ong L, Bu J, Zhu S, Liu R (2007b) Large-scale optical traps on a chip for optical sorting. Appl Phys Lett 90:031107

Suslick K, Fang M, Hyeon T (1996) Sonochemical synthesis of iron colloids. J Am Chem Soc 118(47):11960–11961

Wang Y, Li H, Cao Z, Yu T, Shen Q, He Y (2008) Oscillating wave sensor based on the Goos–H nchen effect. Appl Phys Lett 92:061117

Yang S, Chen Y, Horng H, Hong CY, Tse W, Yang H (2002) Magnetically modulated refractive index of magnetic fluid films. Appl phys lett 81:4931

Yang S, Hsiao Y, Huang Y, Horng H, Hong C, Yang H (2004) Retarded response of the optical transmittance through a magnetic fluid film under switching-on/off external magnetic fields. J Magn Magn Mater 281(1):48–52

Yu T, Li H, Cao Z, Wang Y, Shen Q, He Y (2008) Oscillating wave displacement sensor using the enhanced Goos–H nchen effect in a symmetrical metal-cladding optical waveguide. Opt Lett 33(9):1001–1003

Yuan W, Yin C, Li H, Xiao P, Cao Z (2011) Wideband slow light assisted by ultrahigh-order modes. JOSA B 28(5):968–971